DEVELOPMENT OF A MODEL FOR SUSTAINABLE DECISION-MAKING IN NET ZERO CARBON RETROFITTING OF EXISTING RESIDENTIAL BUILDINGS

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PhD

The Hong Kong Polytechnic University

2026

The Hong Kong Polytechnic University

Department of Building and Real Estate

Development of a Model for Sustainable Decision-Making in Net Zero Carbon Retrofitting of Existing Residential Buildings

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Jul 2025

CERTIFICATE OF ORIGINALITY

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___________________________ (Signed)
Lichini Nikesha Kumari Weerasinghe (Name of Student)

DEDICATION

I dedicate this thesis to my beloved parents (Mr. Janaka Priyashantha Weerasinghe and Mrs. Lakshmi Kumari Athapaththu), my husband (Mr. Aruma Kankani Chamith Maleesha), my father-in-law (Mr. Aruma Kankani Gamini), my mother-in-law (Mrs. Peduru Hewa Mala Lakshmi), my three sisters (Mrs. Ruwangi Rasangika Kumari Weerasinghe, Miss. Wathsala Nethmi Kumari Weerasinghe, and Miss. Githmi Lasakna Kumari Weerasinghe), my brother-in- law (Mr. Manoj Prasad Weerawarna), my niece (Sanuki Sahasna Weerawarna), my nephew (Kevidu Ranuthma Weerawarna), and all other my family members and friends for their huge support in this PhD journey.

ABSTRACT

Net zero carbon (NZC) retrofitting of existing residential buildings contributes to improving occupants' wellbeing and addressing carbon footprint directly and is key to solving the global climate crisis. However, residential building NZC retrofitting is influenced by numerous challenges, and it is difficult to decide the optimal retrofit strategies that maximize social, environmental, and economic sustainability. To effectively retrofit the existing residential buildings to NZC, it is critical to identify the issues and understand the optimal retrofit strategies to enhance social, environmental, and economic sustainability. Therefore, this study aims to develop a model to select the optimal retrofit strategy for maximizing social, environmental, and economic sustainability in residential building NZC retrofitting. To achieve this aim, four objectives were pursued; (1) to analyze and model the challenges and benefits of retrofitting existing residential buildings for NZC, (2) to identify and model the available retrofitting measures to reduce carbon emissions in existing residential buildings, (3) to evaluate the social, environmental, and economic sustainability changes due to retrofitting, and (4) to develop a model to select optimal retrofit strategies for NZC retrofitting of existing residential buildings. This study focused on residential buildings in Hong Kong, since 81% of the existing building stock is residential, representing approximately 27% of energy usage and associated carbon emissions. Consequently, the outcomes of this study contribute to the attainment of NZC from the existing residential buildings in Hong Kong as well as other developed regions. It is worth mentioning that while various studies have investigated the issues addressed in this study, there is a scarcity of research focused on social, environmental, and economic sustainability in achieving NZC residential buildings from the existing buildings in developed regions, particularly in Hong Kong.

A comprehensive literature review was conducted to identify benefits, challenges, and measures for building NZC retrofitting, to identify the focus on social, environmental, and economic sustainability in building NZC retrofitting, and to identify the approaches followed to make optimal decisions on residential building NZC retrofitting. First, questionnaire surveys were conducted with building occupants and experts in Hong Kong to achieve objectives 1 and 2, and the data were analyzed using the mean score ranking method, the Friedman test, and partial least squares structural equation modeling (PLS-SEM). Objectives 3 and 4 were achieved through a case study that was conducted based on a two-person residential unit. Accordingly, multi-objective optimization analysis was conducted using the data collected through simulations, market surveys, and embodied carbon calculations. Finally, a multi-objective optimization model was deployed in the Streamlit framework to automate the multi-objective optimization.

Based on the questionnaire surveys, the study systematically identified key benefits, challenges, and measures for residential building NZC retrofitting in Hong Kong. On the 17 benefits of residential building NZC retrofitting, "*lower building maintenance costs*", "*reduce energy costs*", and "*attractive return on investments*" were identified as the foremost benefits driving residential building NZC retrofitting. In addition, PLS-SEM results demonstrated the significant influence of economic and environmental benefits on residential building NZC retrofitting. On the 28 challenges for residential building NZC retrofitting, "*obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)*", "*difficulties due to high-rise, high-density urban environments*", and "*lack of knowledge and awareness on retrofitting*" were identified as the first three critical challenges. PLS-SEM results demonstrated that "social challenges" and "technical challenges" had a significant impact on residential building NZC retrofitting. On the measures of residential building NZC retrofitting, Friedman test analysis represented occupant's higher preference towards the implementation of renewable energy sources rather than measures on building envelope and energy system upgrades. Furthermore, PLS-SEM analysis results indicated that wall and window retrofitting, HVAC and hot water system retrofitting, and the use of solar energy sources are most suitable for building envelopes, energy system, and renewable energy upgrades in residential building NZC retrofitting.

Based on the findings from the sustainability analysis, the different retrofit strategies showed the highest carbon savings, economic profitability, and occupant satisfaction. Therefore, multi-objective optimization was performed to decide optimal retrofit strategies that maximize carbon saving, economic profitability, and occupant satisfaction. The results indicated that optimal retrofit strategies including 75mm and 100mm wall insulation thickness, 400mm width of wall shading, triple glazed windows with 6mm thick glazing, and 14 number of PV panel installation showed a positive economic profitability percentage range from 129.36% to 133.47%, carbon saving percentage range from 186.90% to 188.58%, and lower values for the predicted percentage of dissatisfaction (PPD) compared to the base case, indicating higher occupant satisfaction. Finally, an automated model was developed by incorporating the multi-objective optimization model into the Streamlit framework to deploy the NZC retrofit decision-making model developed by this study. The two datasets derived from the case study were implemented into the automated model to validate the application's efficacy and responsiveness across a spectrum of different counts of retrofit measures.

Accordingly, the findings of this study contribute significantly to the literature on residential building NZC retrofitting. Further, the models developed to represent the relationship among challenges, benefits, and measures with residential building NZC retrofitting would assists academics, policymakers, decision-makers, advocates, and other stakeholders, particularly in developed regions, in promoting residential building NZC retrofitting to create a zero-emission

sustainable built environment. In addition, the web application developed to make optimal decisions on building NZC retrofitting would contribute to achieving NZC in the building sector. Overall, this study would be advantageous in achieving a zero-emission, sustainable built environment.

Keywords: Benefits; Challenges; Developed regions; Hong Kong; Measures; Net zero carbon (NZC); Residential buildings; Retrofit strategies; Sustainability

PUBLICATIONS ARISING FROM THE THESIS

Refereed Journal Papers (published/ accepted) (2023 – 2025)

Directly Relevant to this Thesis

Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025). Impacts of and relationships between benefits of residential building net zero carbon retrofits. *Smart and Sustainable Built Environment*. 1-25, https://doi.org/10.1108/SASBE-06-2025-0297

Darko, A., **Weerasinghe, L.N.K.**, Chan, A.P.C. (2025). A Partial Least Squares Structural Equation Modeling of Challenges to Existing Residential Building Net Zero Carbon Retrofitting. *Journal of Construction Engineering and Management*. *151* (8). 05025005. https://doi.org/10.1061/JCEMD4/COENG-16471

Weerasinghe, L.N.K., Darko, A., Chan, A.P.C., Blay, K.B., and Edwards, D.J. (2024). Measures, Benefits, and Challenges to Retrofitting Existing Buildings to Net Zero Carbon: A Comprehensive Review. *Journal of Building Engineering*, *94*, 109998. https://doi.org/https://doi.org/10.1016/j.jobe.2024.109998

Others

Weerasinghe, L.N.K., Darko, A., Chan, A.P.C., Xiao, B. (2025). Digital twin for sustainable decision-making in building net zero carbon retrofitting: A systematic review. *Built Environment Project and Asset Management*, 1-17, https://doi.org/10.1108/BEPAM-03-2025-0090

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Refereed Journal Papers (under review for the first or second time)

Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (under review). Modeling the relationship between measures for net zero carbon retrofits of residential buildings. *Building Research and Information,* Ref.: Ms. No. 254464011.

Xiaoyue, Y., Haotian, L., Llewellyn, T., **Weerasinghe, L.N.K.** (under review). Deep reinforcement learning-based multi-objective optimization for building retrofitting: energy, carbon emission, economics, and occupant well-being considerations. *Journal of Building Engineering,* Ref.: Ms. No. JBE-D-25-08793.

Refereed Conference Papers (published/ accepted)

Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025, May). Renewable energy or energy efficiency? Building occupant preferences toward net zero carbon retrofit measures. *World Building Congress 2025*. **Best Paper Award**.

Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2024, February). Net zero carbon retrofitting of existing buildings – A bibliometric study. *In 14th International Conference on Industrial Engineering and Operations Management*, https://doi.org/10.46254/AN14.20240057. **Best Paper Award**.

Refereed Book Chapters (published/ accepted)

Debrah, C., Ohene E., **Weerasinghe, L.N.K**., Darko, A., Chan, A.P.C. (2025). Chapter 9- Green building practices: Integrating sustainability into construction projects. In E. N. Farsangi, M. Noori, T. Y. Yang, V. Sarhosis, S. Mirjalili, & M. J. Skibniewski (Eds.), *Digital Transformation in the Construction Industry* (pp. 165-186). Woodhead Publishing. https://doi.org/https://doi.org/10.1016/B978-0-443-29861-5.00009-3

Zhang, F., Chen, L., Jayasanka, T.A.D.K., **Weerasinghe, L.N.K**., Chan A.P.C. (accepted). Stakeholder Management in Construction in Developing Countries. In *Research companion to advances in construction in the global south*, Elgar Publishing Ltd.

Jayasena, N.S., **Weerasinghe, L.N.K**., Kumaraswamy, M.M. (accepted). Application of Public-Private Partnership in Net Zero Construction Projects. In *Routledge Handbook of Net Zero Construction Project Management*. Routledge

Honour and Award

Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2024, February). Net zero carbon retrofitting of existing buildings – A bibliometric study. The paper was **awarded as the best paper** under the track "Construction Management" on 14th February 2024 at the *14th International Conference on Industrial Engineering and Operations Management*. The conference was held from 11-14 February 2024 at Khalifa University, Dubai, UAE.

Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025, May). Renewable energy or energy efficiency? Building occupant preferences toward net zero carbon retrofit measures. The paper was **awarded as the best paper** under the category "Net zero carbon building design and construction practices" on 21st May 2025 at the *CIB World Building Congress (WBC)*. The conference was held from 19-23 May 2025 at Purdue University, USA.

Full-time PhD Research Studentship for a 3-year PhD research study (January 2023- December 2025). Department of Building and Real Estate. The Hong Kong Polytechnic University, Hong Kong.

ACKNOWLEDGMENTS

This thesis is the result of contributions from many people. I would like to thank everyone for providing me with this opportunity. First, I would like to express my gratitude to the Department of Building and Real Estate of The Hong Kong Polytechnic University for fully funding my Ph.D. study through the Postgraduate Studentship Scholarship.

I would like to offer my heartfelt gratitude to my Chief Supervisor, Prof. Albert P.C. Chan, for his invaluable advice and encouragement throughout my Ph.D. study. Furthermore, I am grateful to my Co-Supervisor, Dr. Amos Darko, for his assistance during my PhD. He has been an excellent anchor and mentor to me. His support helped me throughout my PhD journey. I am incredibly grateful to him. Moreover, I am grateful to Prof. Albert P.C. Chan and Dr. Amos Darko for their time and efforts spent editing and proofreading, and for providing feedback to improve this report and the publications resulting from this study. In addition, I greatly appreciate them granting me the freedom to explore ideas for my study while keeping me on track to obtain reasonable and useful outcomes. I would also like to convey my thanks to the faculty, staff, and research students at the Department of Building and Real Estate of PolyU.

My deepest gratitude goes to my family, especially my mother, father, sisters, brother-in-law, and parents-in-law, for their encouragement and support throughout my life. Specifically, I am so grateful to my husband for his amazing support throughout this journey. His patience and understanding were valuable to me. In addition to my family members, my sincere gratitude goes to my office colleague, Dr. Taiwo Ridwan, for his support and assistance during this research study. Thanks to my friend Dr. Dilakshi Madushika for your endless support and encouragement. I am also grateful to my friend Mrs. Archchana for her support and for sharing the details of the case study used in this study. Last but not least, I thank the building occupants and experts who participated in the questionnaire surveys. I am so grateful to everyone who supported and encouraged me in many ways throughout this PhD journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE[1]

1.0 INTRODUCTION

This chapter provides a quick overview of the thesis. It begins by entering the research's background and disclosing its aim and objectives, designed to fill the identified knowledge gaps. Following that, a clear explanation of the problem statement is provided, outlining the research problems being investigated in this research. Additionally, this chapter provides a concise description of the methodology. The research scope, which defines the study's focus and boundaries, is expanded upon. The chapter concluded by examining the potential significance and implications of the research findings, as well as describing the thesis's organizational structure.

1.1 Research Background

Climate change constitutes a compelling and omnipresent challenge facing humanity today (Silva et al., 2013). It restricts access to essential resources such as land, food, healthcare, and water by worsening severe desertification, crop failures, rising sea levels, and droughts (Edenhofer, 2015). Human activities, particularly the emission of greenhouse gases (GHGs), have indisputably initiated global warming, resulting in a notable increase in the Earth's surface

[1] This chapter is largely based upon:
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025). Critical benefits in retrofitting residential buildings to net zero carbon. *Smart and Sustainable Built Environment*. 1-25.
Darko, A., Weerasinghe, L.N.K., Chan, A.P.C. (2025). A Partial Least Squares Structural Equation Modeling of Challenges to Existing Residential Building Net Zero Carbon Retrofitting. *Journal of Construction Engineering and Management*. *151*(8), 05025005.
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025, May). Renewable energy or energy efficiency? Building occupant preferences toward net zero carbon retrofit measures. World Building Congress 2025.
Weerasinghe, L.N.K., Darko, A., Chan, A.P.C., Blay, K.B., and Edwards, D.J. (2024). Measures, Benefits, and Challenges to Retrofitting Existing Buildings to Net Zero Carbon: A Comprehensive Review. *Journal of Building Engineering*, *94*, 109998.
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2024, February). Net zero carbon retrofitting of existing buildings – A bibliometric study. In 14th International Conference on Industrial Engineering and Operations Management.

temperature above pre-industrial levels (IPCC, 2023). Therefore, recognizing the escalating global warming effect has emphasized the importance of mitigating GHG emissions and addressing environmental change. This incident was further highlighted by the signing of the Paris Agreement in 2015, which aimed to limit the increase of global temperature to 1.5^0C above the preindustrial levels (Song et al., 2022).

However, the world continues to struggle with the challenges posed by the energy crisis and climate change, primarily driven by GHG emissions and high energy consumption (Harkouss et al., 2018). Since carbon is a major participant in the GHGs (Chen et al., 2021), necessary precautions are needed to reduce carbon emissions in order to achieve the Paris Agreement target and mitigate climate change. Accordingly, to limit the increase in global temperature to $1.5\ ^0C$, humanity globally must ultimately achieve net zero or preferably, negative carbon emissions (Azevedo et al., 2021). The Intergovernmental Panel on Climate Change's latest report states that achieving a specific level of limitation on human-included global warming necessitates the restriction of cumulative carbon emissions and the attainment of at least net zero carbon (NZC) emissions, alongside substantial reductions in other greenhouse gas emissions, from a physical science standpoint (IPCC, 2007). In light of these, there is an established connection between climate change and carbon emissions (Walker et al., 2022a).

Across all sectors, buildings stand out as the largest source of carbon emissions, surpassing transportation, agriculture, and manufacturing industries on a global scale (Shen et al., 2022). It has been estimated that buildings account for approximately 40% of the carbon footprint and 30% of global GHG emissions (Shuja et al., 2021). Remarkably, factors such as a growing population, desire for greater comfort, high demand for building services, and spending more time inside the buildings contribute to the significant energy consumption and carbon emissions of the buildings (Chua et al., 2013). Hence, the building sector has emerged as a pivotal player in addressing the pressing issue of climate change (Mokhtar, 2019), leading to a growing focus on transforming the sector into a zero-carbon built environment (Li et al., 2022). As a result, the concept of NZC buildings has become a curious way of achieving zero emissions milestones in the construction sector.

The NZC framework developed by the United Kingdom Green Building Council (UKGBC) defines NZC: for new constructions as “when the amount of carbon emissions associated with a building’s product and construction stages up to practical completion is zero or negative, through the use of offsets or the net export of on-site renewable energy” while NZC: existing buildings defines as “when the amount of carbon emissions associated with the building’s operational energy on an annual basis is zero or negative” (UKGBC, 2019). Currently, many companies, countries, and regions have embarked on initiatives to reduce carbon emissions and attain NZC buildings (Song et al., 2023). For instance, the World Green Building Council, through its global project "Advancing Net Zero," has called for new building constructions to be NZC by 2030, and for all buildings to be NZC by 2050, aligning with the targets outlined in the Paris Agreement (Laski & Burrows, 2017). The United Kingdom has set a goal for all new dwellings to be "zero carbon" by 2016, and carbon emissions ought to be decreased by 80% below 1990 levels by 2050 (Warren et al., 2024).

While attention is rightfully focused on new building constructions, equal emphasis should be placed on existing buildings to reduce their embodied and operational carbon emissions (Heidari et al., 2022). Luo and Oyedele (2021) further explained that buildings that exist in 2050 have already been constructed. Accordingly, the presence of a substantial quantity of existing buildings contributes to a huge amount of carbon emissions, necessitating an urgent need to mitigate the carbon intensity associated with these structures (Zhou et al., 2016). Harkouss et al. (2018) expressed that enhancing energy conservation and carbon reduction in existing buildings are not similar to the new building constructions. Therefore, retrofitting is considered the most feasible method for reducing carbon emissions and improving energy performance in existing buildings (Li et al., 2022). In developed regions such as the European Union, around 70% of construction projects are dedicated to building retrofitting (Piccardo et al., 2020), highlighting the global recognition of retrofitting existing buildings to net zero standards (Ohene et al., 2022b). Therefore, retrofitting existing buildings to reduce their carbon emissions to zero or negative (i.e., NZC retrofitting) is crucial to realizing climate change mitigation.

According to the UKGBC (2019), existing buildings can be retrofitted using energy-efficient measures to reduce carbon emissions and use renewable energy sources to offset the carbon balance in order to achieve NZC. Moreover, in the special issue of the Journal *Energy and Climate Change* on the topic "Net-Zero Energy Systems" Azevedo et al. (2021) describe that domestic carbon emissions are balanced by net-zero energy systems by playing a pivotal role in decarbonization. Accordingly, being retrofitted to NZC means that any emissions of carbon must be counterbalanced in equilibrium with carbon uptake to provide a balance between emissions and removal of carbon. In addition, NZC retrofitting also helps to improve the health and well-being of occupants and reduce resource depletion and waste generation (Ferreira et al., 2017).

However, identifying the retrofit strategy (combination of different retrofit measures) that achieves the greatest reduction in energy use, GHG emissions, and operational costs while aligning with sustainability goals becomes critical in the pursuit of NZC building retrofitting (Egiluz et al., 2021). The reason is that decision-makers have to consider more on social, economic, and environmental sustainability with other factors such as occupant satisfaction to attack the strongest compromise between the requirements of stakeholders and occupants (B.

Wang et al., 2014). In addition, it is imperative for decision-makers to select optimal retrofit options considering carbon emissions, energy consumption, and associated costs (Pluchinotta et al., 2021). Pluchinotta et al. (2021) further detailed that uncertainties related to climate change, building services, and occupant behavior can introduce complexities in retrofitting decisions. However, making informed decisions regarding sustainable retrofitting measures remains critical in minimizing environmental challenges (Sharma et al., 2022). However, lack of interoperability and unstructured decision-making still act as common barriers to the retrofitting of buildings (Ruparathna et al., 2017). Therefore, it is vital to have well-structured decisions on retrofitting existing buildings towards NZC.

1.2 Research Problem Statement

Currently, climate change is the greatest challenge. Existing buildings pose one of the world's most significant challenges in combating climate change. The NZC targets for 2050 make it even more necessary to adapt existing buildings to reduce their carbon emissions to zero or negative. Previous studies have empirically investigated various aspects of NZC retrofitting. For example, Luo (2022) undertook case study research and proposed an integrated design process to select optimal retrofitting measures that achieve net zero energy and carbon while maximizing the lifetime payback cost of a retrofit office building. Furthermore, Zhu (2014) assessed the technical potential of retrofitting measures to renovate office-educational buildings to zero carbon while Charles et al. (2019) evaluated the performance of retrofitting measures to renovate existing office buildings to reduce energy consumption and carbon emissions. Accordingly, most studies have focused on office and education buildings while only limited attempts have focused on the residential buildings (Panagiotidou et al., 2021). In the meantime, CSS (2024) signified the vital need for retrofitting residential buildings to NZC, emphasizing the escalating carbon emissions from residential buildings in line with population growth. Further, the 2025 Global Status Report for Buildings and Construction highlighted that residential buildings account for 15% of global emissions while non-residential buildings account only for 10% (UNEP, 2025). Therefore, it is critical to explore residential buildings retrofitting to NZC.

First, the challenges and benefits of residential building NZC retrofitting were identified and modeled. Previous studies have identified numerous challenges affecting building NZC retrofitting (Attia et al., 2022; D'Agostino et al., 2021). However, studies have focused on the qualitative assessment of these challenges. For instance, the challenges for building retrofitting toward zero-emission in Eastern and Southern Europe, New York, and Canada were assessed by Attia et al. (2017), Attia et al. (2022), Downing and Hsu (2024), and Tsenkova (2021), respectively. Their studies were limited to qualitative assessment of challenges based on experts' perspectives. Even though Satre-Meloy et al. (2024) conducted qualitative and quantitative assessments, their study was limited to the challenge of high upfront costs when retrofitting residential buildings in the United States to zero emissions. Accordingly, the existing studies largely ignored the quantitative assessment of the challenges for residential building NZC retrofitting. In addition, to expedite the NZC retrofitting of residential buildings, a thorough examination of its benefits is imperative. While existing studies have identified various benefits of zero carbon retrofitting (Krarti & Dubey, 2018; Lausselet & Brattebø, 2021; Mavrigiannaki et al., 2021), there remains a gap in quantitatively analyzing these aspects. Understanding the interaction between different benefits is crucial for enhancing the efficacy of achieving NZC in residential buildings (Weerasinghe et al., 2024). Even though previous studies quantitatively evaluated the benefits related to energy consumption, carbon emissions, and cost savings in building retrofitting (Almeida & Ferreira, 2017; Cao et al., 2016; D'Agostino et al., 2021), the quantitative analysis of benefits related to the residential building NZC retrofitting is still lacking in the research domain. Given that occupants are the primary stakeholders impacted by the building's NZC retrofitting (Sleiman et al., 2024), incorporating their viewpoints is imperative in understating the challenges and benefits effectively. Accordingly, there is a need to quantify the correlation between these challenges and benefits in the context of achieving NZC in existing residential buildings based on the occupant's perspectives. To overcome these, a questionnaire was distributed among building occupants to evaluate and model the relationships between the challenges and benefits of the residential building NZC retrofitting, specifically focusing on Hong Kong.

Second, the retrofitting measures used to achieve NZC buildings were identified and modeled. To accomplish NZC in residential buildings, retrofitting efforts must aim to reduce operational carbon emissions through the adoption of energy-effective initiatives while also utilizing sources of renewable energy to offset any of the remaining operational carbon and embodied carbon from retrofitted materials. Azevedo et al. (2021) further emphasized the pivotal role of net zero energy systems in decarbonization efforts by minimizing operational carbon emissions. However, the presence of an expansive array of measures available in the market, encompassing building envelope upgrades, energy system upgrades, and renewable energy upgrades (Weerasinghe et al., 2024), complicates the selection of the most significant retrofitting measures essential for achieving NZC residential buildings. Even though studies have proposed optimized retrofit strategies by combining the retrofitting measures to achieve energy-efficient buildings (Ascione et al., 2020; Hong et al., 2021), a systematic framework for choosing retrofit measures to conduct optimization remains lacking in the achievement of NZC residential buildings. Therefore, this research explored and quantitatively modeled the appropriateness of numerous retrofitting measures associated with the building envelope, energy systems, and renewable energy upgrades on the attainment of NZC status in residential buildings, particularly within the context of Hong Kong.

In addition, due to the availability of different retrofitting measures and their different impacts on the building sub-systems, the selection of suitable retrofitting measures to reduce carbon emissions has become complex (Ma et al., 2012). Even though there are a huge number of retrofitting measures already available in the market, deciding on the most suitable retrofitting measure to achieve social, environmental, and economic sustainability remains a problem. Accordingly, the assessment, identification, and selection of the optimal combination of diverse retrofit measures (retrofit strategy) that can assist in achieving these goals is a difficult decision-making problem that the industry must address. Even though there is much research conducted based on the selection of retrofit strategies focusing on energy efficiency and economic sustainability (Abdelrazek & Yılmaz, 2020; Aguacil et al., 2017; He et al., 2021b), still there is a gap in deciding the optimized NZC retrofit strategies concerning occupants, environmental assessment, and cost. Therefore, this research is an initial step to deciding optimized sustainable (social, environmental, and economic) retrofit strategies to achieve NZC from the existing residential buildings. To this end, a model was developed to select the optimized retrofit strategy concerning economic profitability, carbon emissions, and occupant dissatisfaction using Hong Kong as a case study.

1.3 Research Questions, Aim, and Objectives

1.3.1 Research Questions

The focus of this research is to investigate NZC retrofitting of residential buildings in order to develop a model that facilitates decision-making regarding the NZC retrofitting of residential buildings, encompassing considerations of social, environmental, and economic sustainability. Through a comprehensive exploration and preliminary examination, and building upon the aforementioned background and problems, the subsequent research questions have been formulated to address the identified theoretical gaps:

1. What are the challenges and benefits associated with the NZC retrofitting of existing residential buildings?
2. What are the retrofitting measures that can be used to achieve NZC from the existing residential building?
3. What are the optimal retrofit strategies to achieve NZC residential buildings concerning social, environmental, and economic sustainability, and how can a model be developed to identify these strategies?

1.3.2 Research Aim

This research aims to develop a model to select the optimal retrofit strategy for maximizing social, environmental, and economic sustainability in residential building NZC retrofitting.

1.3.3 Research Objectives

The following objectives were established to achieve the above-mentioned aim.

1. To analyze and model the challenges and benefits of retrofitting existing residential buildings for NZC.
2. To identify and model the available retrofitting measures to reduce carbon emissions in existing residential buildings.
3. To evaluate the social, environmental, and economic sustainability changes due to retrofitting.
4. To develop a model to select optimal retrofit strategies for NZC retrofitting of existing residential buildings.

1.4 Research Scope

This research focused on retrofitting residential buildings to NZC. Geographically, Hong Kong was selected for the research data collection. This study identified the challenges and the benefits of residential building NZC retrofitting and modeled the relationships among challenges and benefits following an empirical analysis. This served as a basis for determining their impact on the residential building NZC retrofitting. Retrofit measures used to achieve NZC were modeled following the same approach, and the findings were used to develop the retrofit strategies employed in achieving NZC. Finally, their social, environmental, and economic sustainability were assessed to develop the model for deciding optimized retrofit strategies to achieve NZC residential buildings.

1.4.1 Why Focus on Residential Buildings?

This research primarily centers on the NZC retrofitting of residential buildings, given their crucial role in supporting daily living and their significant contribution to carbon emissions within the building sector. Accordingly, residential buildings stand out as key players in the climate change narrative. As of 2022, residential buildings were responsible for approximately 5% of direct and 10% of indirect global carbon emissions, making them one of the most substantial carbon-emitting sectors worldwide (UNEP, 2025). The substantial energy consumption for residential heating and cooling, particularly in regions experiencing hot summers and cold winters, leads to significant carbon emissions (Li et al., 2012). The United Kingdom (UK) government also has announced that the UK will not meet the zero emissions target “without near complete decarbonization of the residential building stock”, given that residential buildings accounted for 20% of emissions (Rowe & Rankl, 2024). Thus, addressing NZC in existing residential buildings becomes imperative to combat climate change effectively.

1.4.2 Why Focus on Hong Kong?

Hong Kong, a special administrative region under the governance of the People’s Republic of China, is situated on the southern coast of China to the east of the Pearl River estuary (Figure 1.1).

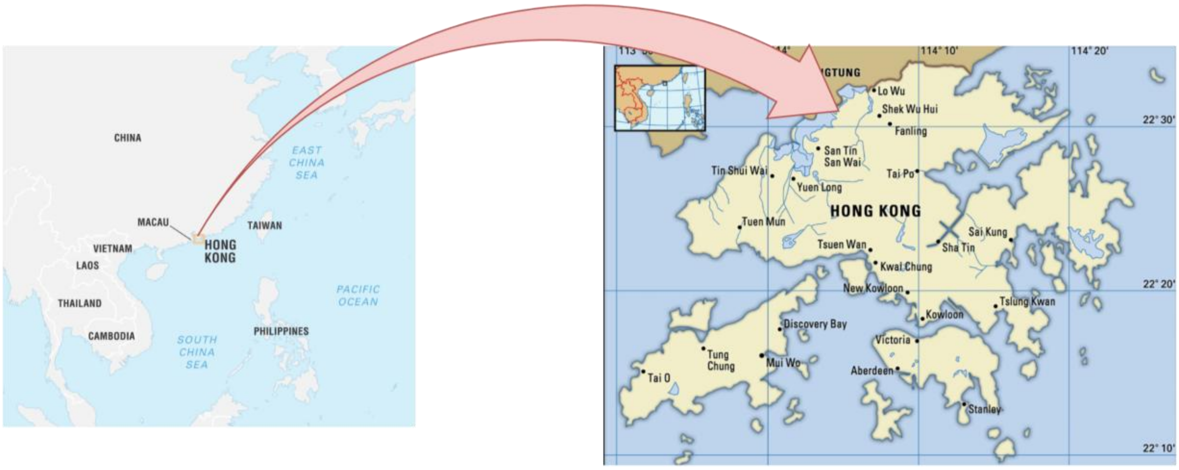

Figure 1.1: Location of Hong Kong (Adapted from (Leung, 2024)).

The region is demarcated by Guangdong Province to the north and the South China Sea to the east, south, and west (Leung, 2024). With a diverse population of approximately 7.4 million individuals from various nationalities (AsianTigers, 2023), Hong Kong spans an area of 1114.57 square kilometers (*Resources - Hong Kong Geographic Data (As at October 2023)*, 2024). Positioned at the northerly periphery of the tropical belt, Hong Kong experiences distinct monsoonal seasonal transitions, characterized by hot, humid summers and cool, dry winters (Leung, 2024), thereby manifesting a humid subtropical climate (AsianTigers, 2023). Given its location in a sub-tropical region marked by prolonged hot seasons and heightened energy consumption for cooling purposes, Hong Kong faces notable challenges in curtailing carbon emissions within its building sector (Pan & Pan, 2019). According to the HK2050isNow (2025), buildings in Hong Kong are accountable for approximately 60% of carbon emissions. Therefore, NZC retrofitting emerges as imperative for Hong Kong to mitigate the adverse impacts of climate change.

Hong Kong, an exceptionally developed region boasting a Human Development Index (HDI) of 0.956, holds the fourth position globally and stands as the sole Asian entity within the top 5 rankings (AsianTigers, 2023). Therefore, the substantial population in Hong Kong correlates with elevated carbon emissions in the region. In addition, Chen et al. (2024) highlighted the fact that the availability of a large stock of existing buildings in developed regions contributes to higher amounts of carbon emissions due to poor energy performance. Hong Kong has more than 50,000 buildings in use, the majority of those older than 30 years (IENV, 2023). Accordingly, they signify the lower energy efficiency standards of the times in which they were built, thus are currently energy inefficient or have poor energy performance. To achieve carbon neutrality before 2050, these buildings need to be retrofitted for energy efficiency on a large scale sooner than later. The Hong Kong Government is also seeking to attain carbon neutrality before 2050 and lower Hong Kong's carbon emissions by 50% before 2035 compared to the 2005 level (GovHK, 2024a). Moreover, most of them are tall buildings in which the daily activities of Hong Kong residents take place. The resulting use of lighting, air-conditioners, lifts, and various electric appliances consumes a large amount of energy. In addition, 81% of the prevailing buildings are residential buildings and they represent approximately 27% of entire energy usage in Hong Kong (IENV, 2023). However, "currently, the energy efficiency of buildings is not optimized to their full extent, and the government policy has been ineffective" (HK2050isNow, 2025). Since operational energy is a main source of carbon emissions from existing buildings, it is necessary to improve energy efficiency within residential buildings to reduce carbon emissions. This can be achieved through the retrofitting of existing residential buildings in Hong Kong. Therefore, this research aimed at retrofitting residential buildings in Hong Kong is timely and significant.

Although there may exist constraints regarding generalizability, a frequent challenge linked to studies concentrated on specific countries, regions, or domains, the examination centered on the developed region of Hong Kong. Consequently, the findings and implications could prove advantageous to policymakers, practitioners, and proponents in other developed regions globally. Nonetheless, conducting similar studies in diverse nations remains essential to consider local circumstances, determine country or market-specific distinctions, and enhance the promotion of NZC retrofitting in residential buildings tailored to distinct national and contextual settings.

1.5 Overview of Research Methodology

This section provides a quick overview of the methodology, whereas Chapter Two explores a detailed explanation of the methodologies used in this research. The fundamental goal of this research is to develop a model that allows the selection of optimized retrofit strategies for residential building NZC retrofitting, with an emphasis on social, environmental, and economic sustainability. Furthermore, the study examined and modeled the relationships between challenges, benefits, and measures for residential building NZC retrofitting. To achieve the research's aim and objectives, a systematic method consisting of five separate stages was implemented, as described below. Figure 1.2 depicts an overview of the research process.

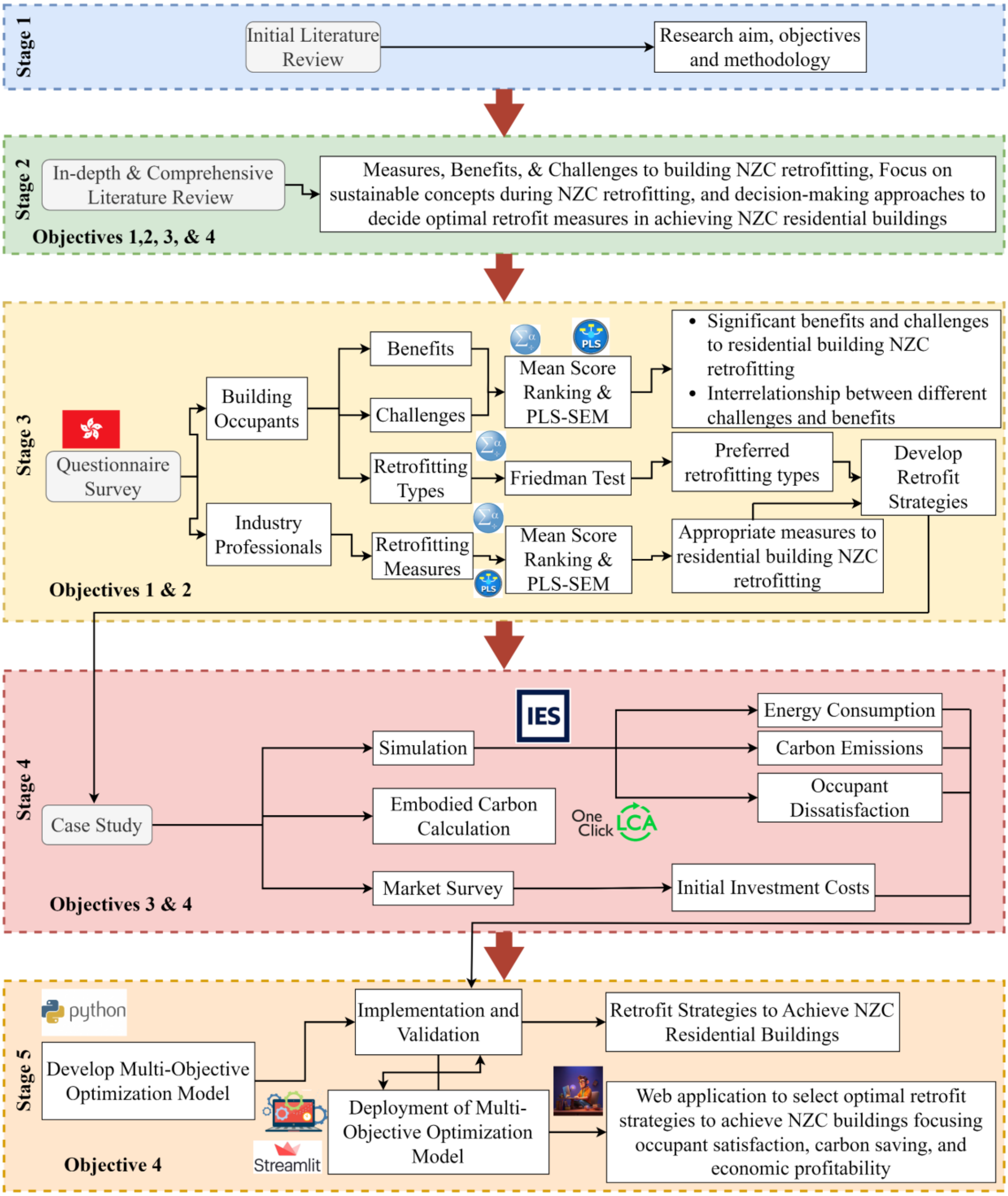

Figure 1.2: Overview of the research process.

Stage 1 initiates the exploration of this research domain through an examination of relevant literature and consultations with supervisors and scholars well-versed in the field. These interactions served to refine the research gap, aim, objectives, and methods. Stage 2 involved an extensive review of literature pertaining to the study's theoretical framework and research goals, drawing from diverse sources like journals, conference papers, books, industry publications, and online repositories. Within this phase, objectives 1, 2, and 3 saw partial fulfillment as key factors essential for their achievement were identified in the literature review process.

Moving on to stage 3, primary data collection was executed via two structured questionnaire surveys, targeting both building occupants and experts. These surveys aimed to assess the benefits and challenges of NZC retrofitting in residential buildings and to pinpoint specific retrofitting measures. The quantitative analysis and model development based on the collected data in this stage facilitated the complete attainment of objectives 1 and 2. Analytical tools such as partial least squares structural modeling (PLS-SEM), the Friedman test, and the mean score ranking method were employed, as depicted in Figure 1.2 and detailed in Chapter Two.

In stage 4, data from a case study building was used for simulation. Integrated Environmental Solutions Virtual Environment (IESVE) served as the simulation tool to gather insights on energy usage, carbon emissions, and occupant dissatisfaction. The One Click LCA software aided in calculating the embodied carbon of retrofitting strategies, while a market survey was conducted to reveal initial investment costs for retrofit strategies, thereby fully addressing objective 3 and partially attending to objective 4. Finally, in stage 5, objective 4 was entirely achieved by developing and deploying multi-objective optimization models to determine retrofit strategies concerning carbon emissions, economic profitability, and occupant dissatisfaction.

1.6 Significance and Contribution of Research

Despite numerous endeavors within academia and the built environment aimed at addressing climate change, a notable dearth of research exists concerning the retrofitting of existing residential buildings towards NZC. The retrofitting of existing residential buildings presents a formidable challenge in climate change mitigation, due to the population growth and the substantial energy demands necessary for ensuring occupant comfort. Consequently, the imperative to retrofit these residential buildings becomes paramount. Furthermore, the retrofit process must not only consider environmental impacts and cost-effectiveness but also prioritize occupant satisfaction, a facet that has received limited attention within academic discourse. Hence, the outcomes of this research serve as an initial step towards bringing this scholarly void, laying the groundwork for future investigations aimed at achieving NZC residential buildings.

The theoretical contribution of this research includes the identification of challenges, benefits, and measures specific to NZC retrofitting of existing residential buildings. Further, this research evaluates the relationships between challenges as well as benefits specific to Hong Kong. Further, the findings of the research initially attempt to model the relationship among numerous retrofitting measures to achieve NZC residential buildings in Hong Kong. Hence, this research acts as a forerunner in advancing the exploration of NZC retrofitting for residential buildings, an area that currently lacks extensive study.

Practical implications involve the recognition of significant challenges, benefits, and measures that necessitate consideration prior to embarking on NZC. In addition, the developed multi-objective optimization model can be used by them in making social, environmental, and economic sustainable decisions on NZC retrofitting which is still lacking in the construction industry. Further, policymakers can utilize the quantitative findings of this research to develop strategies that promote NZC in the construction industry. Even though this research primarily focused on Hong Kong, the implications and findings of this research could be valuable to academics, practitioners, policymakers, and advocates in other developed regions worldwide. Ultimately, the outcomes of this research contribute to achieving a zero-emissions built environment, supporting the goals of the Paris Agreement.

1.7 Structure of the Thesis

This thesis comprises ten chapters. Chapter 1 serves as an introduction, defining key terms, outlining the study's scope, explaining the research problem, and establishing research questions, aims, and objectives. Chapter 2 delves into a comprehensive literature review concerning the challenges, benefits, and measures of NZC building retrofitting, exploring sustainable considerations in academia for such retrofit processes. A concise overview of the research methodology is presented, with a more detailed discussion found in Chapter 3. Chapters 4 to 6 detail the empirical findings derived from PLS-SEM, mean score ranking, and the results of Friedman test, focusing on challenges, benefits, and measures of residential building NZC retrofitting. In Chapter 7, the formulation of retrofit strategies is discussed alongside simulation results, embodied carbon assessments of these strategies, and insights from the market survey. Chapter 8 covers the analysis of carbon savings, economic profitability, and occupant satisfaction related to the proposed retrofit strategies. Chapter 9 showcases the development and deployment of a multi-objective optimization model aimed at determining optimal retrofit strategies concerning social, environmental, and economic sustainability for achieving NZC in existing residential buildings. Finally, Chapter 10 concluded the thesis, highlighting its limitations and offering recommendations for future endeavors.

1.8 Chapter Summary

This chapter introduced and established the background of the research. It revealed the rationale underpinning the study, concluding the identification of its aim and objectives. Additionally, a summary of the methodology and the research's significance is included. The thesis's structure is outlined, with the subsequent chapter delving into the research methodology utilized in this research.

CHAPTER TWO[2]

2.0 LITERATURE REVIEW

2.1 Introduction

Upon introducing the research in Chapter 1, the current chapter reviews the retrofitting of existing residential buildings towards NZC. The first section of the literature review explored the existing residential building retrofitting to NZC, considering the benefits, challenges, and numerous measures. The review then moved its focus to the social, economic, and environmental sustainability considerations and optimal decision-making approaches for residential building NZC retrofitting from prior building retrofitting research. Following the literature review, the study identified the knowledge gaps in the domain and developed a conceptual framework integrating the study's objectives. Then the chapter concludes with a comprehensive summary of its content.

2.2 Retrofitting Existing Residential Buildings to Achieve NZC

The process commonly referred to as retrofitting, also known as refurbishment or renovation in the literature (Fawcett & Killip, 2014), is widely recognized as an effective strategy for

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[2] This chapter is largely based upon:
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025). Critical benefits in retrofitting residential buildings to net zero carbon. *Smart and Sustainable Built Environment*. 1-25.
Darko, A., Weerasinghe, L.N.K., Chan, A.P.C. (2025). A Partial Least Squares Structural Equation Modeling of Challenges to Existing Residential Building Net Zero Carbon Retrofitting. *Journal of Construction Engineering and Management*. *151*(8), 05025005.
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025, May). Renewable energy or energy efficiency? Building occupant preferences toward net zero carbon retrofit measures. World Building Congress 2025.
Weerasinghe, L.N.K., Darko, A., Chan, A.P.C., Blay, K.B., and Edwards, D.J. (2024). Measures, Benefits, and Challenges to Retrofitting Existing Buildings to Net Zero Carbon: A Comprehensive Review. *Journal of Building Engineering*, *94*, 109998.
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2024, February). Net zero carbon retrofitting of existing buildings – A bibliometric study. In 14th International Conference on Industrial Engineering and Operations Management.

reducing energy consumption and carbon emissions from existing building stocks (Felius et al., 2020). Given the pressing issue of climate change and the substantial contribution of existing residential buildings to carbon emissions through energy usage, retrofitting represents a pertinent course of action (Almeida et al., 2018). Khoukhi et al. (2020) have detailed that retrofitting the existing building is frequently more cost-effective than constructing a new one. In addition, retrofitting, renovating, or refurbishing interventions have the potential to improve energy performance by limiting energy usage and carbon releases within existing residential buildings (Kutty et al., 2023). Herrera-Avellanosa et al. (2020) further asserted that retrofitting existing buildings has the possibility to significantly decrease carbon releases. In addition, Luo and Oyedele (2021) proved that retrofitting buildings is crucial for achieving net-zero carbon goals.

Retrofitting existing residential buildings is not only an important aspect of dealing with the avoidance of climate change but also fosters a sustainable relationship with our environment (Ferreira et al., 2017). The authors further explained that NZC retrofitting is particularly significant, as it not only decreases carbon emissions by improving the overall energy efficiency of the built environment but also mitigates resource depletion and waste production associated with new construction. Therefore, striving for NZC residential buildings within the global building stock becomes essential for addressing multifaceted concerns such as global warming, resource management, energy security, and resilience (Miller et al., 2018).

2.2.1 Benefits of Retrofitting Residential Buildings to NZC

In comparison to energy-efficient residential buildings, NZC retrofitted residential buildings offer a multitude of benefits. Even though energy-efficient endeavors contribute to achieving NZC status in existing residential buildings, it is important to distinguish between energy-efficient residential buildings and NZC-retrofitted residential buildings (Fogarty, 2021). NZC-retrofitted residential buildings consistently demonstrate high energy efficiency. According to Fogarty (2021), the significance of NZC retrofitted residential buildings goes beyond mitigating operational carbon emissions resulting from operational energy in existing residential buildings. These retrofitted buildings also address the crucial aspect of embodied carbon related to retrofit materials, which is often overlooked in energy-efficient retrofitting. Therefore, NZC buildings largely impact to enhance environmental sustainability by reducing the carbon footprint. As a result, NZC-retrofitted buildings contribute to establishing a more sustainable built environment compared to energy-efficient buildings. Accordingly, NZC-retrofitted buildings achieved the overall figure of sustainability improving environmental and economic feasibilities and the health and well-being of building occupants (Versteegden, 2023). Therefore, retrofitting existing buildings to NZC has advanced benefits and previous studies have investigated these in different ways. Most studies have identified the benefits as direct benefits and co-benefits (Almeida & Ferreira, 2017, 2018; Lausselet & Brattebø, 2021). However, Ferreira et al. (2017) classified the benefits into building quality, user wellbeing, and economics, while Rose et al. (2019) classified them into building quality, direct economic, and user comfort. Based on these classifications and literature findings, this study has classified the NZC retrofitting benefits into social, environmental, and economic benefits (refer to Table 2.1).

Table 2.1: Benefits of residential building retrofitting towards NZC (See Weerasinghe et al., 2024).

Category	Benefits	Sources
Social benefits	Improve building comfort (thermal, natural, lighting, acoustic, etc.)	[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14]
	Enhance the quality of life for occupants	[6, 9, 10, 13, 15, 16]
	Increase efficiency and reliability of the building systems	[16]
	Provide better building appearance/ aesthetics	[1, 3, 5, 6, 9, 17]
	Increase building usable time	[5, 7]
	Increase indoor and outdoor environmental quality	[7, 8, 13, 15, 17]
	Create new job opportunities	[1, 13, 15, 18, 19]
Environmental benefits	Reduce environmental pollution	[1, 3, 6, 13, 15, 20, 21]
	Reduce energy consumption and secure energy supply	[1, 2, 4, 9, 11, 13, 14, 16, 19, 21]

Economic benefits	Reduce carbon and GHG emissions	[1, 4, 8, 8, 12, 13, 15, 16, 18, 19, 21]
	Minimize adverse climatic effects	[1, 4]
	Increase the building value	[1, 6, 7, 12]
	Reduce energy costs	[3, 4, 6, 7, 8, 10, 13, 15, 18, 21]
	Increase accessibility to incentives and subsidies	[12, 15]
	Lower building maintenance costs	[1, 5, 7, 15, 16]
	Attractive return on investments	[6, 10]
	Reduce vulnerability to fluctuating prices	[13]

References: 1. Almeida and Ferreira (2018), 2. Athienitis et al. (2018), 3. Bal et al. (2021), 4. Boeri et al. (2016), 5. Capeluto (2019), 6. Christensen et al. (2014), 7. Danial et al. (2023), 8. Fawcett and Killip (2014), 9. Gajić et al. (2021), 10. Jones et al. (2013), 11.Kutty et al. (2023), 12.Luddeni et al. (2018), 13.Rose et al. (2019), 14. Skandalos and Karamanis (2021), 15. Ferreira et al. (2017), 16. Mavrigiannaki et al. (2021), 17. Abreu et al. (2019), 18. Krarti and Dubey (2018), 19. Pan and Pan (2019), 20. Alabi et al. (2020), 21. Wu (2022)

Social or occupants' benefits are one of the most predominant categories of benefits pertaining to the retrofitting of buildings to NZC. According to Table 2.1, numerous authors have acknowledged that enhancing building comfort is a notable social benefit associated with NZC retrofitting (Luddeni et al., 2018; Skandalos & Karamanis, 2021). Christensen et al. (2014) expounded that building retrofitting can significantly improve aesthetic appearance which often poses a challenge to the retrofitting efforts. Furthermore, Krarti and Dubey (2018) have highlighted that retrofitting can create additional employment opportunities by reducing unemployment rates and enhancing a country's economy.

Environmental benefits are the primary and direct benefits derived from the NZC retrofitting and foremost amongst these are the reduction of energy consumption and carbon emissions (Almeida & Ferreira, 2017; Rose et al., 2019). By achieving these benefits, buildings will automatically contribute to the reduction of environmental pollution arising from the operation of the existing buildings. Further, NZC retrofitting directly contributes to mitigating adverse climatic effects (Boeri et al., 2016). Thus, if people were expediting the retrofitting of buildings to NZC, it would be possible to address the significant challenges posed by adverse climate change. Reduced energy cost is the most significant economic benefit of NZC retrofitting as per Table 2.1. In addition, it enables the mitigation of vulnerability to fluctuate energy prices with the establishment of a user-friendly comfort zone within the building (Rose et al., 2019) and increases property value (Almeida & Ferreira, 2018).

Recent studies have attempted to prove the benefits of NZC retrofitting through various case studies. Capeluto (2019) showed that facade retrofitting can enhance the energy efficiency and user comfort of existing buildings. Charles et al. (2019) demonstrated energy and carbon savings and return on investment through a case study of office buildings and focused on the retrofitting of the wall, roof, and windows, and simulating onsite renewable energy sources. Wu (2022) evaluated the economic and environmental benefits of NZC retrofitting through a case study of high-end hotels and focused on air conditioning, domestic hot water, heating and lighting systems, and kitchen equipment retrofitting. Despite various studies attempting to verify the NZC retrofitting benefits through case studies, there remains a notable research gap to quantify the benefits and evaluate the interrelationships between them. Moreover, to promote NZC retrofitting, strategies must be devised to increase the awareness of building owners and occupants towards the benefits

2.2.2 Challenges for Retrofitting Residential Buildings towards NZC

Despite the palpable benefits of residential building NZC retrofitting, various challenges hinder NZC retrofitting adoption. According to Miglani (2023), the Real Estate industry encounters significant challenges in implementing NZC retrofitting due to labor shortages, rising costs, and misinterpretation among building owners. In addition, a substantial global investment of approximately US$3 trillion is required to tackle the challenges associated with NZC retrofitting, including addressing knowledge gaps, the inadequacy of experts, and technological issues (Miglani, 2023). Therefore, identifying, understanding, and addressing these challenges is critical to promoting residential building NZC retrofitting. Abreu et al. (2019) identified the challenges from the perspective of homeowners, while Attia et al. (2017) and Attia et al. (2022)

explained that there are economic, social, and technical challenges to residential building NZC retrofitting. G. Liu et al. (2020) categorized the challenges into administration, finance, knowledge/information, and technology challenges, while Marinelli et al. (2021) categorized them into technical, economic, and regulatory challenges. Based on the different classifications, this study categorized challenges for residential building NZC retrofitting into social, financial, industrial and stakeholder, administrative, technical, and geographical challenges as listed in Table 2.2.

Table 2.2: Challenges for residential building NZC retrofitting (See Weerasinghe et al., 2024).

Category	Challenges	Sources
Social challenges	Resistance to change	[1, 2, 3, 4]
	Doubts regarding energy savings	[1, 5, 6, 7]
	Unwillingness to invest in retrofitting	[5]
	Lack of knowledge and awareness on retrofitting (i.e., measures, benefits, and market)	[2, 8, 9, 10, 11, 12, 13, 14, 15]
Financial challenges	Uncertainty about payback time or return on investment	[1, 3, 7, 13, 16, 17]
	High initial cost	[3, 6, 7, 10, 11, 14, 16, 18, 19, 20, 21, 22]
	Complicate access to the finance data	[4, 10, 23]
	Lack of incentives and financial support	[3, 13, 15, 17, 20]
Industrial and Stakeholder challenges	Lack of reliability of the stakeholders who execute the work	[1, 17, 24]
	Uncertainty about available technologies	[11, 26]
	Lack of collaboration among stakeholders	[14, 17, 21, 23, 24, 25]
	Lack of professional knowledge and skills	[4, 10, 11, 12, 13, 17, 20, 24, 25]
	Poor understanding of sustainability and net zero targets	[4, 20, 24]
	Fragmentation of the supply chain	[10, 17]
	Lack of promotion	[13, 17]
Administrative challenges	Lack of government support	[20, 21]
	Complex permit procedures	[10, 21]
	Unavailability of standardized approaches to prevent climatic variations	[10]
	Lack of coordination mechanism	[13, 27]
	Lack of continuity, consistency, and flexibility of retrofit policies	[13, 28]
	Lack of effective strategic programs	[12]
	Conflict with other building codes and regulations	[4]
	Complexity of existing buildings	[11, 17, 18]

Technical challenges	Lack of data and information	[10, 18, 26, 29]
	Lack of widespread adoption of energy efficiency, renewable, and smart technologies	[10]
Geographical challenges	Variation in climatic conditions	[7]
	Difficulties due to high-rise, high-density urban environment	[4]
	Obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)	[4]

References: 1. Abreu et al. (2019), 2. Albrecht and Hamels (2021), 3. Almeida and Ferreira (2018), 4. Bjørberg and Salaj (2023), 4. Pan and Pan (2019), 5. Adan and Fuerst (2015), 6. Galvin (2014), 7. Wang et al. (2022), 8. Aldossary et al. (2015), 9. Brás (2017), 10. D'Agostino et al. (2021), 11. Davies and Osmani (2011), 12. Gajić et al. (2021), 13. G. Liu et al. (2020), 14. Ohene et al. (2023), 15. Patterson (2016), 16. Christensen et al. (2014), 17. Prieto et al. (2023), 18. Amoruso and Schuetze (2022a), 19. Aparicio-Gonzalez et al. (2020), 20. Butt et al. (2021), 21. Mavrigiannaki et al. (2021), 22. Norton et al. (2021), 23. Ascione et al. (2017), 24. Cromwijk et al. (2017), 25. Jankovic et al. (2021), 26. Affandi et al. (2022), 27. Kharlamova et al. (2016), 28. Herrera-Avellanosa et al. (2020), 29. Marinelli et al. (2021).

2.2.2.1 Social Challenges

The critical social challenge in converting existing residential buildings to NZC is the general public's limited knowledge and awareness of available retrofitting measures, the market, and their concomitant benefits (Brás, 2017; Davies & Osmani, 2011; Patterson, 2016). Abreu et al. (2019) identified that the public exhibits reluctance to change their attitudes towards retrofitting due to confusion surrounding energy saving and carbon emissions reductions. Consequently, the public is unwilling to invest their funds in NZC retrofitting, posing a significant challenge to the adoption of NZC. Therefore, it has become imperative to develop an integrated strategy to promote the significance of converting existing residential buildings to NZC - aiming to overcome social challenges.

2.2.2.2 Financial Challenges

Literature findings highlighted that high initial cost is the most critical challenge. Albrecht and Hamels (2021) revealed that half of European households face financial constraints that impede their ability to retrofit existing buildings to NZC. Since existing residential buildings are old buildings, high initial costs occurred due to the building assessments, sustainable material procurement, and NZC retrofitting designs (Bui et al., 2023b). In addition, the public exhibits uncertainty about the return on investment and the payback period (Abreu et al., 2019). According to the research by Luo (2022), the economic analysis reveals that the installation of photovoltaic (PV) panels for residential building NZC retrofitting would require a payback period exceeding 12 years to recover the initial investment costs while wind turbines require more than 11 years. In light of that, capital plays a pivotal role in achieving NZC retrofitted residential buildings. Hence, government financial support through incentives, low-interest bank loans, and grants would be essential in the NZC retrofitting of existing residential buildings. Therefore, authorities must admit that NZC retrofitting does not pay back and should focus upon mitigating these financial challenges through the development of detailed cost guidelines from both the market and the government, thus enabling easy access to financial information.

2.2.2.3 Industrial and Stakeholder Challenges

As presented in Table 2.2, numerous challenges emerge within industry and among stakeholders who are directly and indirectly participating in the transformation of existing residential building stock towards NZC. The most significant barrier that hinders the adoption of NZC residential buildings is the unavailability of skilled experts in the industry (Butt et al., 2021; Davies & Osmani, 2011; Prieto et al., 2023). Pan and Pan (2019) also have identified a lack of industrial skilled laborers and a poor understanding of the sustainability and net zero targets highly affecting the delivery of NZC buildings. In addition, the collaboration of stakeholders is essential to delivering NZC buildings as they are the main promoters of zero-carbon buildings. However, less collaboration has been identified by Cromwijk et al. (2017) while retrofitting the buildings to NZC. Apart from those, the lack of reliability of the stakeholders who execute the work, uncertainty on the available technologies, fragmentation of the supply chain, and lack of available promotion platforms for retrofitting of existing buildings act as challenges for converting the existing residential buildings to NZC. The development of a strong supply chain with industry experts such as facility managers, engineers, clients, and building users and the involvement of the government to guide and train stakeholders for NZC retrofitting would support reducing the industrial and stakeholder challenges and promote the NZC concepts.

2.2.2.4 Administrative Challenges

The role of policies and regulations is crucial in the retrofitting process of existing residential buildings to achieve NZC. They serve as a roadmap for stakeholders involved in the conversion of existing residential buildings to NZC. However, the lack of stability, reliability, and flexibility of retrofit policies has been identified as an administrative challenge for the conversion of existing residential buildings to NZC (Herrera-Avellanosa et al., 2020; G. Liu et al., 2020). Other than that, less support from the government, complex permit procedures, and lack of coordination mechanisms significantly affect the conversion of existing residential buildings to NZC, as in Table 2.2. Even though there are many challenges related to administration, having a strong supply chain involving experts and the government would be highly supportive of impeding the administrative challenges and retrofitting the existing residential building stock to achieve net zero targets.

2.2.2.5 Technical Challenges

Insufficient data and information on existing residential buildings pose a significant challenge in NZC retrofitting (Amoruso & Schuetze, 2022a). The achievement of NZC in retrofitting existing residential buildings necessitates upgrades to the building envelope and energy systems to reduce operational carbon emissions. Therefore, obtaining relevant information concerning the existing buildings, such as insulation, thermal bridging, HVAC systems, and lighting, is essential (Moschetti et al., 2019). However, the aging of these buildings poses a challenge in retrieving such technical details (Moghaddasi et al., 2021). Additionally, Li et al. (2022) emphasized the limited availability of information from suppliers regarding retrofitting materials, which is essential for calculating the embodied carbon associated with achieving NZC. Furthermore, Heidari et al. (2022) mentioned the challenges arising from information gaps, emphasizing the need for such data to calculate embodied carbon and conduct building assessments. This need was exemplified through a case study of retrofitting a residential building in Canada with the aim of achieving a zero-carbon footprint. In addition, Amoruso et al. (2018) explained the prebound effect, which describes the condition prior to the retrofit, signifying the extent to which energy consumption is lower than predicted (Sunikka-Blank & Galvin, 2012), needs to be considered while calculating the energy savings before retrofitting. If not, the presence of uncertainties for the actual energy consumption of the buildings increases the investment risk for the NZC measures. To this end, advancements in technologies such as lasers and scanners can be utilized to evaluate the actual energy consumption and carbon emissions before and after retrofitting. Therefore, the expansion of professional's knowledge and experience with modern technologies would help to enhance the process of NZC retrofitting. In addition, building complexity and limited adoption of smart technologies hinder the delivery of NZC residential buildings (D'Agostino et al., 2021). Space limitations and structural considerations highly impacted the installation of renewable energy sources to achieve NZC residential buildings (Kim et al., 2021). Athienitis et al. (2018) have explained that the implementation of serial retrofitting can offer a more economical approach to achieving net zero target while addressing technical challenges. This has been supported by their case study, which describes the use of a series of PV panels integrated into the building facade.

2.2.2.6 Geographical Challenges

Pan and Pan (2019) identified geographical problems with domestic renewable energy as a key challenge for promoting zero-carbon residential buildings in Hong Kong. Furthermore, Wang et al. (2022) noted that climate changes further limit the application of retrofitting measures. The residential building's capacity to harness sunlight and wind energy is highly affected while applying renewable retrofitting measures. Moreover, the high density of the buildings in the urban areas is also identified by Pan and Pan (2019) as a geographical challenge to retrofit the residential buildings for NZC.

2.2.3 Measures to Retrofit Existing Residential Buildings to NZC

NZC retrofitting can serve various purposes, including achieving green energy and zero-emissions goals (Khoukhi et al., 2020). Ma et al. (2012) explained retrofitting measures as energy conservation measures employed to advance building energy efficiency and promote sustainability. Since the ultimate goal of retrofitting existing residential buildings to achieve NZC is the complete elimination or reduction of carbon emissions associated with the operational energy to zero or negative (UKGBC, 2019), the implementation of energy-efficient measures serves to mitigate the carbon emissions resulting from excessive energy consumption while ensuring the utilization of low/zero carbon sources within the building to optimize energy performance (Roche, 2017). In addition, given that operational energy constitutes a major contributor to carbon emissions in existing residential buildings (Besana & Tirelli, 2022), it becomes crucial to decrease energy consumption and assess the energy performance of existing residential buildings to successfully attain the NZC target. Hill et al. (2020) further explained that energy-efficient measures are employed as essential measures for NZC in order to decrease energy consumption and optimize energy performance, thereby mitigating the demand for energy and reducing costs associated with the utilization of renewable energy sources. Accordingly, renewable energy sources play an important role in reaching the NZC target by enabling optimized energy performance within the residential building (Yu & Ho, 2021). Therefore, as a result of undergoing NZC retrofitting, residential buildings inherently contain energy-efficient characteristics, demonstrating the concept of zero-energy residential buildings emerges as a possible method to achieve the NZC target.

Although zero energy attempts are supported to achieve decarbonization efforts from operational energy (Liang et al., 2022), it is crucial to consider the lifecycle impact of the retrofit materials in order to reach NZC by retrofitting the existing residential buildings (Satola et al., 2021). Merely attaining NZC from the existing residential buildings may not be successful if the carbon emissions associated with the retrofit materials throughout their entire lifespan are not considered (Tirelli & Besana, 2023). Therefore, to genuinely achieve NZC, it is imperative to identify and address the carbon impact of the retrofit materials over their complete lifecycle, potentially through the implementation of offsetting measures (Y. Liu et al., 2023). Hence, to accomplish NZC status for buildings within the existing stock, it is imperative to address both the minimization of carbon emissions from the operational energy and the embodied carbon associated with retrofitting materials.

Accordingly, considering the zero-emissions goal of existing buildings, retrofitting measures can be classified into two major groups *viz*.: (1) energy saving measures, such as envelope upgrades; and (2) those that supply energy, such as renewable energy systems (UKGBC, 2019). Energy-saving measures can be further classified into active and passive measures (D'Agostino et al., 2021). Passive measures include changes to the building envelope through, for example, insulation and shading, while active measures refer to changes to the active building energy systems, such as lighting and HVAC systems (D'Agostino et al., 2021; El-Sherif et al., 2020). Besides, retrofitting measures can be classified based on the amount of energy savings and carbon emissions reduction, as minor, major, and deep measures, where deep retrofitting measures are highly influenced to achieve NZC residential buildings (Ruparathna et al., 2017). However, most studies have classed NZC retrofitting measures into envelope, energy system, and renewable energy upgrades (Hill et al., 2020; Liang et al., 2022; Yu & Ho, 2021), which are adopted in analyzing the literature in this study.

2.2.3.1 Building Envelope Upgrades

A plethora of previous studies focused on building envelope upgrades to achieve NZC (Ferreira et al., 2017; Heidari et al., 2022; Luo, 2022). Retrofitting the roof, walls, floors, doors, and windows is a good example of such upgrades. Insulation and vegetation are significant measures for roofs and walls to reduce residential building heat loss (Boeri et al., 2016; Bui et al., 2023a; Ferreira et al., 2017). Vegetation not only augments residential building heating and cooling activities but also improves air quality and water efficiency (Berardi et al., 2017). However, envelope upgrades have been mainly focused on the roof (Luo & Oyedele, 2021), wall (Shadram et al., 2020), and floor (Ferreira et al., 2014) insulation but also, window-to-wall ratios (Krarti & Dubey, 2018), door and window glazing types and their thicknesses (Luo & Oyedele, 2021), and shading (Bui et al., 2023a).

Controlling heat transference within the residential building is a significant output from retrofitting building components. Therefore, the thermal conduction, convection, and radiation properties of materials are important parameters that must be considered when retrofitting residential building components. The use of dynamic windows, including automated solar-tracking (Capeluto, 2019) and gas-filled doors and windows (Colclough et al., 2022; Xu et al., 2023) are mentioned as methods to improve solar heat transmission and reduce energy demand for lighting and cooling. Insulation materials such as extruded polystyrene and fiberglass are highlighted for their role in heat energy transfer and storage in roofs, walls, and floors (Albatayneh, 2021; Ascione et al., 2019b; Gao et al., 2023). Shadram et al. (2020) claimed cellulose is the best insulation material for roofs, from the perspective of life cycle energy while Abdou et al. (2021) indicated the minimum thickness required for energy-efficient insulation.

2.2.3.2 Energy System Upgrades

Energy system upgrades refer to the retrofitting of HVAC, hot water and lighting systems. Measures can be grouped into two dichotomous categories *viz*.: (1) improvements to the current energy systems; and (2) replacement with more energy-efficient systems. The first category includes adjusting heating and cooling set points (Krarti & Dubey, 2018), improving natural ventilation and daylighting (D'Agostino et al., 2021), and controlling the lighting level and operation of equipment (Ruparathna et al., 2017). The second category includes the use of new central heating systems (Almeida & Ferreira, 2017), and highly efficient boilers and cooling sources (Ascione et al., 2015), installation of the domestic hot water system (Hamburg et al., 2020) and replacement of light bulbs and electrical appliances (Heidari et al., 2022). Some studies support the benefits of these measures, such as the potential 37% reduction in energy consumption through HVAC system replacement (Khoukhi et al., 2020) and the 65% lighting energy savings achieved by integrating lighting controls in appropriate conditions (daylighting control) (D'Agostino et al., 2021). Adjustment of the heating and cooling set point is also highlighted as a low/no cost measure that yields significant energy savings and carbon reduction (Heidari et al., 2022).

2.2.3.3 Renewable Energy Upgrades

Renewable solar and wind energy have been widely used as retrofitting measures to achieve NZC. Renewables can generate more energy without carbon emissions within the building through PV systems on the roof, facade, or shading (Heidari et al., 2022; Hirvonen et al., 2021; Rafique & Williams, 2021), or through installing wind turbines (Abdou et al., 2021; Luo & Oyedele, 2021). Previous studies have primarily focused on the performance of these retrofitting measures together with the environmental impacts and economic feasibility. For example, Kutty et al. (2023) and Luddeni et al. (2018) analyzed the energy-saving capabilities of PV systems in existing buildings, while AlAjmi et al. (2016) examined the economic viability, energy saving, and carbon reduction potential of PV and solar cooling systems. Skandalos and Karamanis (2021) investigated energy saving, and CO_2 reduction achieved by integrating PV into the windows and the shading.

In addition to onsite renewable sources, offsite renewable sources also contribute to offsetting carbon emissions and achieving NZC buildings. These offsite renewable sources are situated away from the existing buildings, and building users can procure renewable energy from these sources to offset their carbon emissions, thus progressing towards NZC (Thomas et al., 2018). Luo (2022) explained the significance of carbon offsetting in attaining NZC in retrofitted buildings. Carbon offsetting involves purchase or investment in renewable energy projects as compensation for the generated carbon emissions (Lo, 2023). Accordingly, offsetting balances carbon emissions by allocating funds to renewable energy projects, thereby reducing the overall carbon content in the atmosphere. Therefore, while offsite renewable energy sources supply energy to buildings to reduce operational carbon emissions, offsetting counterbalances these emissions by investing in renewable energy projects. In this way, renewable sources play a pivotal role in achieving NZC from the existing residential buildings.

Following the analysis of NZC retrofitting measures, Table 2.3 provides a list of measures implemented in previous studies. This offers researchers, policymakers, and practitioners a valuable reference to measures that can be implemented in retrofitting and converting existing residential buildings to ones of NZC status.

Table 2.3: Retrofitting measures to achieve NZC residential buildings (See Weerasinghe et al., 2024).

Retrofitting Type	Building Element/ System/ energy	Retrofitting Measure	Sources

Envelope upgrades	Roof	1	Add insulation (i.e., extruded polystyrene, fiberglass, aerogel, cellulose, rock wool, polyisocyanurate, mineral wool, and change U values)	[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34]
		2	Apply a layer of black high-density polyethylene (HDPE) net with 90% shading as a roof cover	[35]
		3	Ceiling insulation	[29, 35]
		4	Apply vegetation (green roof)	[10, 36, 37]
		5	Implementation of a roof plastering with low solar absorptance (i.e., implementation of a cool roof)	[5, 36]
		6	Apply cement tile or light-colored linoleum-pressed steel sheet	[18]
	Wall	7	Facade insulation	[6, 8, 10, 16, 17, 32, 38, 39, 40, 41, 42]
		8	Add insulations (i.e., phase change material insulation, Polyisocyanurate, Silicone- vacuum insulation panels, extruded polystyrene, expanded polystyrene, rock wool, aerogel, cork)	[3, 5, 9, 11, 12, 13, 15, 16, 18, 19, 21, 22, 23, 25, 26, 27, 28, 30, 31, 33, 34, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53]
		9	Aerogel plaster on the external wall	[42]
		10	Adding vapor barriers to the facade	[10]
		11	Apply shadings (i.e., fins, overhang)	[5, 10, 36, 38, 54]
		12	Green facade	[43]
		13	Apply thermal plasters	[7]
	Windows	14	Install double-glazed windows	[10, 14, 19, 22, 25, 26, 27, 28, 31, 32, 37, 38, 39, 46, 49]
		15	Replace windows with low U-value windows	[6, 11, 14, 17, 33, 43, 49]
		16	Install triple-glazed windows	[14, 21, 25, 26, 28, 39, 42, 49, 55, 56]
		17	Dynamic window replacement module, which includes automated solar-tracking blinds for shading control with night-insulation properties	[57]
		18	Install automatic shading devices above the windows	[54]
		19	Fill argon gas between two layers of glass	[34, 46, 54, 56]
		20	Apply thin film coating on the windows	[37, 58]
		21	Use of energy-efficient glazing (low e values)	[5, 7, 10, 12, 18, 23, 24, 28, 34, 37, 50, 56, 59]

		22	Use polyvinylchloride (PVC) window frame with double glazing	[5, 16, 45]
		23	Use PVC window frame with triple glazing	[51]
		24	Sealings of windows and joint places	[53]
		25	Adjust window to wall ratio	[24, 34, 60]
	Door	26	Upgrade double-glazed PVC units with air-filled gaps	[14]
		27	Replace with new energy-efficient doors	[23]
		28	Use double-glazed doors	[32]
	Floor	29	Add insulation	[16, 17, 25, 27]
Energy system upgrades	HVAC system	30	Apply new central heating systems	[10, 38]
		31	Adjust the heating and cooling set point in an efficient way	[24, 34, 41]
		32	Use a ventilation system with heat recovery ventilation	[32, 41, 45, 53, 55, 56, 61, 62]
		33	Use of efficient heat pumps (i.e., ASHP, GSHP, geothermal heat pump, hybrid heat pumps)	[41, 49, 53, 61, 62, 63, 64, 65]
		34	Use high-efficiency boilers and cooling sources	[7, 8, 11, 12, 16, 27, 43, 62, 65, 66]
		35	Update HVAC system (i.e., control air and water distribution, use the best strategy for chillers, improve the heat pumps, turn off chillers during non-occupied periods, use high-efficiency HVAC systems, replacement of air handling units)	[2, 5, 10, 12, 16, 19, 49, 62, 67, 68]
	Hot water system	36	Install a DHW	[12, 16, 17, 21, 38, 56, 60, 67]
		37	Use an electric water heater	[41]
	Lighting system	38	Replacement of light bulbs with efficient bulbs (LED, Fluorescent)	[8, 10, 12, 19, 37, 40, 41, 44, 53, 55, 56, 59, 61, 62, 69, 70]
		39	Control the lighting level and equipment operation (i.e., use daylight sensing light controls)	[2, 21, 24, 31, 48, 59, 69]
		40	Improve natural ventilation and lighting	[55]
Renewable energy upgrades	Solar energy	41	Install PV Pannels (i.e., for electricity generation)	[1, 5, 6, 8, 10, 11, 12, 13, 16, 17, 20, 21, 23, 26, 27, 28, 31, 34, 37, 38, 40, 41,

			43, 44, 45, 49, 51, 54, 55, 60, 61, 62, 64, 65, 66, 67, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87]
	42	Install solar thermal collectors (i.e., for DHW production)	[8, 13, 17, 19, 21, 23, 27, 28, 38, 40, 43, 45, 53, 55, 60, 62, 66, 67, 85, 88]
Wind energy	43	Install wind turbine	[1, 27, 28, 84]

References: 1. Abdou et al. (2021), 2. AlAjmi et al. (2016), 3. Albatayneh et al. (2020), 4. Asaee et al. (2019), 5. Ascione et al. (2019b), 6. Ascione et al. (2021), 7. Ascione et al. (2015), 8. Asdrubali et al. (2019), 9. Barlow and Fiala (2007), 10. Bui et al. (2023a), 11. Charles et al. (2019), 12. Cho et al. (2020), 13. Ciardiello et al. (2020), 14. Colclough et al. (2022), 15. Fawcett and Killip (2014), 16. Ferreira et al. (2014), 17. Ferreira et al. (2017), 18. Gao et al. (2023), 19. Garriga et al. (2020), 20. Gremmelspacher et al. (2021), 21. Hamburg et al. (2020), 22. Hamza et al. (2022), 23. Hirvonen et al. (2021), 24. Krarti and Dubey (2018), 25. Lingard (2021), 26. Luddeni et al. (2018), 27. Luo (2022), 28. Luo and Oyedele (2021), 29. Miller et al. (2018), 30. Rose et al. (2019), 31. Ruparathna et al. (2017), 32. Shadram et al. (2020), 33. Thomas et al. (2018), 34. (Xu et al., 2023), 35. Tuck et al. (2020), 36. Berardi et al. (2017), 37. Li et al. (2018), 38. Almeida and Ferreira (2017), 39. Almeida et al. (2018), 40. Corvacho et al. (2016), 41. Heidari et al. (2022), 42. Hosseini et al. (2020), 43. Boeri et al. (2016), 44. Cellura et al. (2017), 45. Giuseppe et al. (2017), 46. Gugul et al. (2018), 47. Jiang et al. (2023), 48. Li et al. (2013), 49. Li et al. (2022), 50. Morelli et al. (2012), 51. Panagiotidou et al. (2021), 52. Walker et al. (2022b), 53. Wang et al. (2022), 54. Zhu (2014), 55. D'Agostino et al. (2021), 56. Salem et al. (2019), 57. Capeluto (2019), 58. Cuce et al. (2021), 59. Chung and Rhee (2014), 60. Carpino et al. (2017), 61. Borghi et al. (2021), 62. Norton et al. (2021), 63. Bennett et al. (2022), 65. Rafique and Williams (2021), 66. Boardman (2007), 67. Assimakopoulos et al. (2020), 68. Vakalis et al. (2021), 69. Barbosa and Azar (2018), 70. Koo et al. (2014), 71. Aldossary et al. (2017), 72. An et al. (2023), 73. Asaee et al. (2017), 74. Athienitis et al. (2018), 75. Bal et al. (2021), 76. Chang et al. (2022), 77. Crespi et al. (2021), 78. Duckers and Hasanah (2020), 79. Emil and Diab (2021), 80. Fawcett (2014), 81. Fong and Lee (2012), 82. Fonseca et al. (2018), 83. Guerra-Santin et al. (2018), 84. Jones et al. (2013), 85. Kristjansdottir et al. (2016), 86. Shakouri et al. (2022), 87. Stefanović et al. (2014), 88. Silva et al. (2013).

Since energy represents the primary driver of carbon emissions in existing buildings, a wide range of retrofitting measures outlined in Table 2.3 are available to facilitate the achievement of NZC residential buildings. However, while using these measures to reduce the operational carbon emissions from the existing residential buildings, it is vital to consider the embodied carbon associated with the retrofitting materials (retrofitting measures) to achieve the NZC target. Therefore, there is no way of retrofitting the existing residential buildings to NZC without considering the lifecycle carbon emissions associated with the retrofitting materials as depicted in Figure 2.1.

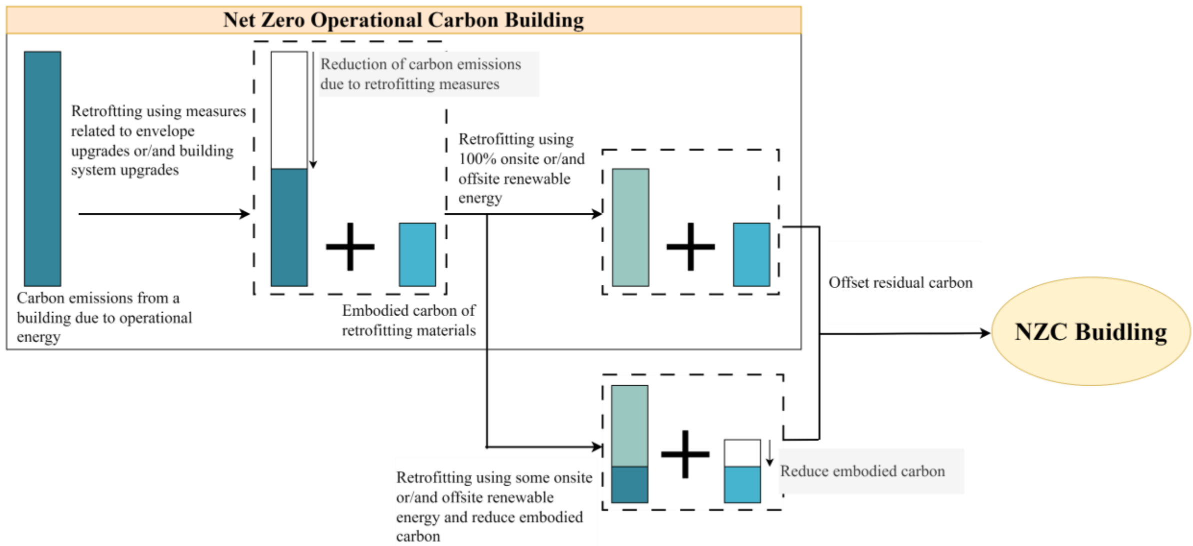

Figure 2.1: Use of retrofit measures to achieve NZC residential buildings (Weerasinghe et al., 2024).

2.2.4 Gaps in Knowledge

After a comprehensive literature review, Weerasinghe et al. (2024) identified that understanding the interaction between different benefits and challenges is crucial for enhancing the efficacy of achieving NZC in residential buildings. While existing studies have identified various benefits (Krarti & Dubey, 2018; Lausselet & Brattebø, 2021; Mavrigiannaki et al., 2021) and challenges (Attia et al., 2022; D'Agostino et al., 2021) of residential building NZC retrofitting, there remains a gap in quantitatively analyzing these aspects. Given that occupants are the primary stakeholders impacted by the building's NZC retrofitting (Sleiman et al., 2024), incorporating their viewpoints is imperative in understanding the benefits and challenges effectively. Therefore, this study quantitatively analyzes the benefits and challenges of residential building NZC retrofitting using the data collected through a questionnaire among building occupants.

Further, Weerasinghe et al. (2024) identified numerous measures to retrofit residential buildings to NZC and categorized them as building envelope upgrades, energy system upgrades, and renewable energy upgrades. The availability of various measures complicates the selection of the most significant retrofitting measures essential for achieving NZC residential buildings. Even though studies have proposed optimized retrofit strategies by combining the retrofitting measures to achieve energy-efficient buildings (Ascione et al., 2020; Hong et al., 2021), quantitative evaluation of retrofit measures which are useful in developing the retrofit strategies, is still lacking in the achievement of NZC residential buildings. Accordingly, this study explores and quantitatively models the appropriateness of numerous retrofitting measures associated with the building envelopes, energy systems, and renewable energy upgrades on the attainment of NZC status in residential buildings through a questionnaire survey conducted among building occupants and experts.

The outcomes of this study are anticipated to offer important information for policymakers and practitioners, aiding in the reassessment of NZC retrofitting benefits, challenges, and measures, and the formulation of effective policies and strategies to advance carbon neutrality within the built environment.

2.3 Sustainability Concepts during NZC Retrofitting of Existing Residential Buildings

Establishing sustainability is widely acknowledged as a comprehensive approach to addressing environmental, economic, and social challenges (GhaffarianHoseini et al., 2013). Consequently, retrofitting emerges as a significant strategy for the construction industry to enhance social, environmental, and economic sustainability. However, in order to uphold this concept, it is imperative to make sustainable decisions throughout the process of NZC retrofitting as depicted in Figure 2.2.

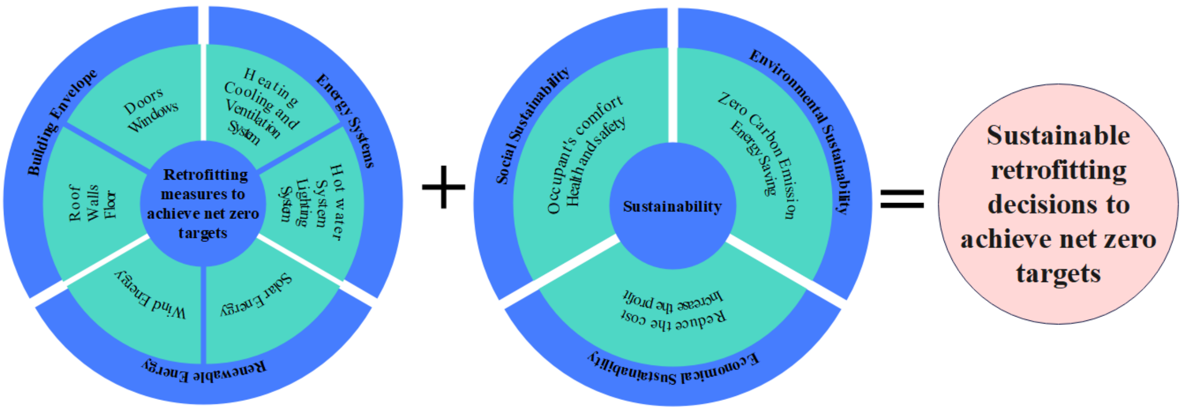

Figure 2.2: Process of achieving sustainability in NZC retrofitting.
Source: Author's

The following Table 2.4 provides a summary of the literature review focusing on sustainable concepts considered in previous studies.

Table 2.4: Focus on sustainability when retrofitting residential buildings to NZC.

Literature Source	Sustainable Concepts Environmental sustainability	Economic sustainability	Social sustainability
Jenkins (2010)	✓	✓	
Fong and Lee (2012)	✓		
Morelli et al. (2012)	✓		
Silva et al. (2013)	✓	✓	
Ferreira et al. (2014)	✓	✓	
Corvacho et al. (2016)	✓	✓	
Kristjansdottir et al. (2016)	✓	✓	
Asaee et al. (2017)	✓	✓	
Brás (2017)	✓		
Camporeale et al. (2017)	✓	✓	
Carpino et al. (2017)	✓		
Almeida and Ferreira (2017)	✓	✓	
Krarti and Dubey (2018)	✓	✓	
Guerra-Santin et al. (2018)	✓		
Almeida et al. (2018)	✓	✓	
Gugul et al. (2018)	✓	✓	
Li et al. (2018)	✓		
Asaee et al. (2019)	✓	✓	
Alabi et al. (2020)	✓	✓	
Tuck et al. (2020)			✓
Shadram et al. (2020)	✓		
Garriga et al. (2020)	✓	✓	
Albatayneh (2021)	✓		✓
Assimakopoulos et al. (2021)	✓		✓
D'Agostino et al. (2021)	✓	✓	

Hirvonen et al. (2021)	✓	✓	
Cerezo-Narváez et al. (2021)	✓	✓	
Jankovic et al. (2021)	✓		
Lingard (2021)	✓	✓	
Panagiotidou et al. (2021)	✓	✓	
Rafique and Williams (2021)	✓	✓	
Almutairi et al. (2022)	✓		
Heidari et al. (2022)	✓		
Wang et al. (2022)	✓	✓	
Walker et al. (2022a)	✓		
Bennett et al. (2022)	✓		
Amoruso and Schuetze (2022b)	✓	✓	
Gao et al. (2023)	✓	✓	✓
Razzaq et al. (2023)	✓	✓	
Jiang et al. (2023)	✓	✓	
Kutty et al. (2023)	✓		

According to Table 2.4, all the studies have focused on environmental sustainability, as reducing carbon emissions and energy consumption are the primary goals when retrofitting residential buildings to NZC. Even though there have been numerous studies focused on economic sustainability, only a few have concentrated on social sustainability, which symbolizes the building occupant's comfort and satisfaction. In addition, only the study conducted by Gao et al. (2023) have focused on the triple bottom line of sustainability by considering all three social, environmental, and economic sustainability as shown in Figure 2.2, when making decisions for residential building retrofitting to achieve NZC.

2.3.1 Environmental Sustainability

The primary objectives of retrofitting existing residential buildings to achieve net-zero targets revolve around reducing energy consumption and eliminating carbon emissions (Shen et al., 2022). As a result, it becomes crucial to conduct an environmental analysis to assess the sustainability of the buildings before and after the retrofitting process (Asdrubali et al., 2019). Table 2.4 provides evidence that the majority of the existing studies on residential building retrofitting have primarily focused on the aspect of environmental sustainability.

Walker et al. (2022a) analyzed the robustness of different retrofit strategies focusing on six different contexts in Europe and concluded that the robustness of retrofit strategies is context dependent. Further, they stated that lowering GHG emissions from operational activities is insufficient for achieving zero emissions, embedded emissions from materials must also be considered to attain environmental sustainability. Brás (2017) provided an approach to predict the years required to eliminate the embodied carbon of wall retrofitting materials. Even though they identified that reducing embodied carbon associated with retrofitting materials is essential in attaining NZC while fulfilling environmental sustainability needs, their study has limited the focus on wall retrofitting materials.

In reaching zero-carbon residential buildings, it is critical to consider occupant behavior, just as it is with energy efficiency and carbon emissions. Fong and Lee (2012) investigated the effect of PV installation on roofs and walls in subtropical regions to achieve zero-energy residential buildings, and they found that occupant behavior has a significant impact on reducing energy consumption and carbon emissions. Agreeing with that, Carpino et al. (2017) demonstrated the direct influence of occupant behavior on plants and equipment utilization, as well as internal gains such as temperature set point, lighting, and ventilation. Further, Guerra-Santin et al. (2018) noticed prebound effects on energy performance if the occupant's behavior is not considered while retrofitting the buildings. Therefore, when retrofitting residential buildings, it is necessary to examine the embodied carbon with retrofit materials as well as occupant's behavioral patterns in order to achieve zero-carbon buildings while attaining environmental sustainability goals.

2.3.2 Economic Sustainability

Building retrofit projects encompass a range of objectives, including the reduction of environmental impacts, enhancement of occupant comfort and well-being, and the mitigation of economic consequences such as utility expenses and maintenance costs (Xu et al., 2011). Consequently, past researchers have underscored the importance of considering economic feasibility when selecting retrofit measures for existing residential buildings. Corvacho et al. (2016) demonstrated that in regions where space heating energy usage constitutes a minor proportion of total energy consumption, the financial viability of thermal insulation for residential buildings may be limited due to extended payback periods. Nevertheless, they highlighted substantial financial gains achievable through the upgrade of inefficient household appliances and the substitution of traditional light bulbs with LED ones. Wang et al. (2022) introduced a decision-making tool tailored for homeowners to ascertain cost-optimal retrofit measures by evaluating factors of initial investment, energy saving, carbon emission reduction, discounted payback period, and bill reductions. Moreover, Ferreira et al. (2014) proposed an innovative methodology for determining the cost-optimal level when selecting retrofit measures for transitioning existing residential buildings to NZC, while Asadi et al. (2023) conducted a parallel investigation utilizing the RETROSIM proprietary optimization engine. In addition, the assessment of cost efficiency in retrofit strategies has been scrutinized through diverse metrics, including payback period (Corvacho et al., 2016), net present value (Camporeale et al., 2017), and life cycle cost (Panagiotidou et al., 2021). Accordingly, it is evident that most of the previous studies have concentrated on economic sustainability features while attaining the NZC from the existing residential buildings.

2.3.3 Social Sustainability

The social component of the sustainable development concept focuses on vital characteristics of humanity such as living conditions, comfort, health, and well-being to advance the goal of sustainability (Vallance et al., 2011). Since the building is planned and built to be inhabited by humans, occupancy standards need to be satisfied to safeguard the standard of existence, happiness, and wellness of its occupants (Nimlyat & Kandar, 2015). Therefore, the impact on the occupants needs to be given top priority while retrofitting the existing buildings towards a net zero target. Hence, retrofitted buildings should provide a better indoor environment for the occupants by increasing their comfort levels and promoting wellness. As a result, it is necessary to be concerned with social sustainability before making decisions on retrofitting existing buildings towards the net zero targets.

Tuck et al. (2020) assessed the thermal comfort levels while retrofitting with high-density polyethylene (HDPE) nets as roof covers for shading, along with free-running ventilation throughout the day and insulation above the ceiling in residential buildings in hot–humid climate regions to overcome thermal discomfort. They proposed it as a very suitable method for residential houses with roof tile in hot, humid climate regions to achieve zero emissions and occupant comfort through a low-cost method. Further, Albatayneh (2021) introduced a methodology for determining optimal parameters for the building envelope of single-storey residential buildings, aimed at reducing heating and cooling energy consumption while ensuring occupant's thermal comfort. In the meantime, Gao et al. (2023) developed a comprehensive framework to make decisions on residential building retrofits, considering the aspects of occupant comfort, carbon emissions, and global costs focusing on all three sustainable features which are still lacking in the NZC retrofitting domain. However, as per Table 2.4, there is a notable deficiency in the emphasis on social sustainability, particularly regarding occupant comfort, health, and well-being while retrofitting residential buildings to NZC.

2.3.4 Gaps in Knowledge

Retrofitting is widely regarded as the most effective strategy for transforming existing residential building stock into NZC buildings, while simultaneously addressing the triple bottom line of sustainability. Consequently, retrofitting represents a critical pathway toward a sustainable future. However, despite its sustainable nature, existing studies have often neglected to fully embrace the comprehensive definition of sustainability. While sustainable retrofitting necessitates the fulfillment of three key concepts (social, environmental, and economic), many studies have focused solely on environmental sustainability or environmental sustainability and economic/social sustainability. Table 2.4 reveals a predominant emphasis on environmental and economic sustainability in the decision-making procedure regarding retrofitting existing residential buildings. However, it is vital to recognize that building occupants, as the ultimate users of the buildings, permit equal attention to their comfort, health, and well-being during the retrofitting process. Accordingly, similar to the significance attributed to economic and environmental sustainability, the incorporation of social sustainability becomes a key aspect when formulating decisions pertaining to residential building retrofitting. Therefore, this study efforts to bridge this gap by explicitly considering the triple bottom line of sustainability as depicted in Figure 2.2, when making retrofitting decisions toward achieving the NZC target.

Accordingly, this study developed a model to make sustainable decisions on retrofit strategies to achieve NZC from existing residential buildings. To attain that, this study evaluates the carbon emissions, profitability, and the percentage of occupant dissatisfaction associated with different retrofit strategies through a case study to attain the environmental, economic, and social sustainability in NZC retrofitting. Therefore, the outcome of this study would offer value for industry practitioners while deciding optimal retrofit strategies for residential building NZC retrofitting, focusing on the triple bottom line of sustainability.

2.4 Optimal Decision-making Approaches Focusing on Residential Building NZC Retrofitting

Simulation and optimization have been widely used in construction for various purposes, including improving energy efficiency, cost efficiency, thermal comfort assessments, and designing new constructions (Nguyen et al., 2014). Optimization is considered a process of finding solutions for a problem with one or more objectives (Sharif & Hammad, 2019). The optimization process with one objective is defined as single-objective optimization while multi-objective optimization has more than one objective. Table 2.5 illustrates an overview of the recent publications focused on optimization approaches to make decisions on residential building retrofitting to reduce carbon emissions.

Table 2.5: Overview of recent optimal decision-making approaches focused on residential building NZC retrofitting.

Authors	Focus of the study	Objectives	Algorithms	Tools
Magnier and Haghighat (2010)	Proposed GAINN to process optimization of thermal comfort and energy consumption in residential buildings	Thermal comfort and energy consumption	NSGA II	TRNSYS, MATLAB, and GAINN
Penna et al. (2015a)	Examination of how incentives for various energy efficiency measures can enhance the effectiveness of optimal retrofit solutions	Energy consumption, net present value, indoor thermal discomfort	NSGA II	TRNSYS
Penna et al. (2015b)	The determination of optimal retrofit options in terms of either maximum economic efficiency or minimum energy consumption toward zero energy building behavior for the lowest possible thermal discomfort	Energy efficiency, global cost, and thermal discomfort	NSGA II	TRNSYS
Ascione et al. (2019a)	Development of a multi-objective optimization approach to address energy efficiency and cost-optimality in residential building retrofitting	Primary energy consumption and global cost	Genetic algorithm (GA)	EnergyPlus and MATLAB
Salata et al. (2020)	Explored the optimal solutions to retrofit the existing buildings based on energy consumption, carbon emission, and costs	Annual energy consumption, installation cost, and carbon emission	NSGA II	EnergyPlus
Amani et al. (2024)	Development of a framework to reduce energy consumption in	Annual energy consumption and	NSGA II	Design Builder,

	buildings focusing on external wall insulation	environmental effects of materials	EnergyPlus, SimaPro, and MATLAB

Amani et al. (2024) proposed wall insulation is an optimal measure to retrofit the residential buildings in Karaj, Iran to reduce energy consumption and global warming potential from the retrofit materials. Even though their study has focused on external wall retrofitting, they proposed that the developed framework can be used in selecting optimal retrofit strategies for building retrofitting concerning carbon analysis. Salata et al. (2020) developed an optimization approach to reduce the annual energy consumption of the existing residential buildings, focusing on energy, financial, and environmental criteria. Their study incorporated evolutive computation techniques, a subset of artificial intelligence, in conjunction with energy analysis software such as EnergyPlus, and genetic algorithms programmed in Python to ascertain retrofit strategies for existing residential buildings. During the optimization process, each retrofit made to the building's envelope or systems was linked to a gene within the context of genetic algorithms. Accordingly, Salata et al. (2020) recommended that these types of technologies support making solutions for the complex issues faced during residential building retrofitting, related to energy, carbon, cost, and climate change.

Further, Magnier and Haghighat (2010) have developed a decision-making approach through optimization focusing on thermal comfort and energy consumption in retrofitting residential buildings while Ascione et al. (2019a) focused on primary energy consumption and global costs. Accordingly, most of the studies have focused on two objectives while making optimal decisions on retrofitting residential buildings to reduce energy consumption and carbon emissions. However, Penna et al. (2015a) and Penna et al. (2015b) have focused on energy, cost, and thermal comfort criteria while deciding optimal retrofit strategies. Even though those studies developed decision-making approaches using different technologies for modeling, simulation, and optimization, most of the studies have primarily focused on energy consumption to achieve zero energy residential buildings from the existing building stocks. Since there is a significant difference between zero-energy and zero-carbon residential buildings, it is necessary to conduct more studies focusing on decision-making approaches to decide optimized retrofit strategies to achieve NZC residential buildings from the existing buildings.

2.4.1 Gaps in Knowledge

The variety of available retrofit measures on the market, combined with varying decision-making criteria, complicates the process of retrofitting residential buildings to NZC. While many studies have focused on decision-making approaches for building retrofitting to achieve zero-energy buildings, retrofitting buildings to NZC provides comparatively more benefits in terms of reduced energy consumption, carbon emissions, and embodied carbon in retrofit materials. However, beyond carbon considerations, financial feasibility and occupant satisfaction are critical objectives to consider when retrofitting residential buildings to NZC. As a result, determining optimal retrofit strategies becomes complex when considering carbon, costs, and occupant satisfaction in the pursuit of NZC residential buildings. Given the increased complexity that comes with a larger set of objectives, a gap in the literature exists for decision-making approaches directed to the selection of optimal retrofit strategies that account for carbon considerations, costs, and occupant satisfaction. This study seeks to fill this gap by developing a model to guide the identification of optimal retrofit strategies, with a focus on maximizing carbon saving and economic profitability while minimizing the occupant average dissatisfaction during the retrofitting of existing residential buildings to NZC. The proposed model is intended to be a useful tool for industry professionals, allowing them to make decisions on optimal retrofit strategies for building retrofitting to NZC.

2.5 Conceptual Framework

According to the literature review, the existing residential buildings are accountable for greater levels of carbon emissions and energy consumption, resulting in adverse effects such as climate change, resource depletion, air pollution, and waste generation. Retrofitting existing residential buildings to NZC is an efficient way to lower carbon emissions and energy consumption while preventing environmental issues. The literature review identified numerous factors that impact residential buildings NZC retrofitting as benefits, challenges, and measures. Benefits have a positive impact on retrofitting residential buildings toward NZC and serve as motivators. However, challenges as constraints have a negative influence on residential building NZC retrofitting while measures serve as implementors with a positive impact. After assessing these benefits, challenges, and measures, the study modeled them to demonstrate their significance for retrofitting residential buildings to NZC.

Further, retrofit measures were combined to develop retrofit strategies and conducted a case study to evaluate their social, environmental, and economic sustainability. Finally, the study developed a decision-making model to decide optimized retrofit strategies concerning social, environmental, and economic sustainability in achieving NZC residential buildings. Figure 2.3 illustrates the conceptual framework that represents the connection between research objectives.

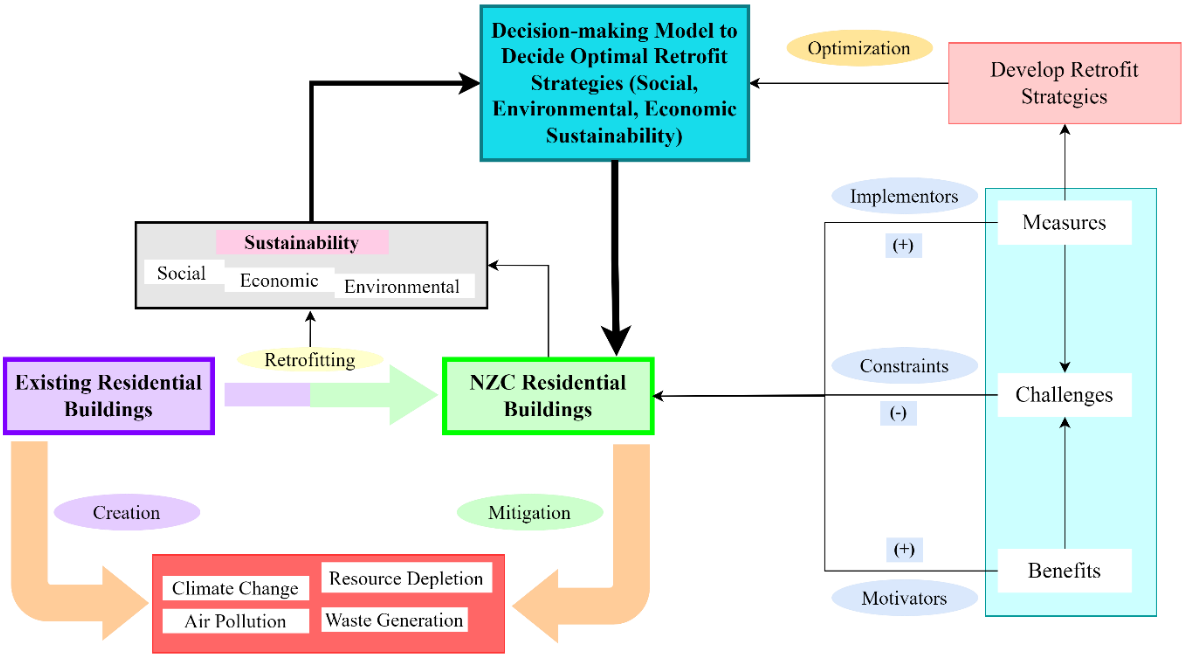

Figure 2.3: Conceptual framework demonstrating the connection between research objectives. Source: Author's own development.

2.6 Chapter Summary

This chapter provided the findings of the literature related to the study's objectives. This was supported to identify knowledge gaps prevailing in the domain of residential building retrofitting to NZC. Finally, the chapter developed a conceptual framework to demonstrate the connections between the objectives of this study. However, the factors identified as benefits, challenges, and measures were used for the development of the questionnaire to collect data from building occupants and experts. The next chapters will discuss the findings of the data analysis in achieving the study's objectives.

CHAPTER THREE[3]

3.0 RESEARCH METHODOLOGY

3.1 Introduction

This chapter delineates the methodologies employed in conducting the study. The establishment of a robust research methodology is essential for achieving the study's aims and objectives, as well as substantiating its findings. This chapter elucidates the research methods, emphasizing their strengths and weaknesses, along with the rationale behind their selection.

Prior studies in the realm of construction management have utilized a variety of methodologies encompassing interviews, questionnaires, and case studies (Adabre et al., 2021; Chan et al., 2018; Darko et al., 2018; Ohene et al., 2024). Building upon this precedent, the present study employed the questionnaire survey and case study as primary data collection methods to address the identified research problems. Section 3.4 expounds on the questionnaire survey, while Sections 3.5 and 3.6 delineate the methodologies employed for analyzing the questionnaire data and providing details of the respondents, respectively. Section 3.7 elaborates on the methodologies and software utilized in analyzing the case study data. Accordingly, this

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[3] This chapter is largely based upon:
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025). Critical benefits in retrofitting residential buildings to net zero carbon. *Smart and Sustainable Built Environment*. 1-25, https://doi.org/10.1108/SASBE-06-2025-0297.
Darko, A., Weerasinghe, L.N.K., Chan, A.P.C. (2025). A Partial Least Squares Structural Equation Modeling of Challenges to Existing Residential Building Net Zero Carbon Retrofitting. *Journal of Construction Engineering and Management*. *151*(8), 05025005.
Weerasinghe, L.N.K., Darko, A., Chan, A.P.C., Blay, K.B., and Edwards, D.J. (2024). Measures, Benefits, and Challenges to Retrofitting Existing Buildings to Net Zero Carbon: A Comprehensive Review. *Journal of Building Engineering*, *94*, 109998.
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025, May). Renewable energy or energy efficiency? Building occupant preferences toward net zero carbon retrofit measures. World Building Congress 2025.
Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2024, February). Net zero carbon retrofitting of existing buildings – A bibliometric study. In 14th International Conference on Industrial Engineering and Operations Management.

chapter incorporates detailed descriptions of the methods and analytical approaches employed in the study.

3.2 Research Methods

The primary data collection methods employed in this study encompassed an extensive literature review, questionnaire surveys, and a case study. After the literature review, two questionnaire surveys were administered to the intended population to quantitatively analyze the benefits, challenges, and measures pertinent to residential building NZC retrofitting. The mean score ranking method and PLS-SEM were utilized to analyze the data on benefits, challenges, and measures associated with residential building NZC retrofitting. Supplementary statistical analyses, such as the Shapiro-Wilk test, were conducted as needed for quantitative analysis.

The case study was instrumental in gathering data on energy performance for subsequent energy simulations. Sustainability analysis methods were used to analyze the data derived from the case study, and the derived data from the case study was applied to validate the developed multi-objective optimization models. Table 3.1 provides a summary of the data collection and analysis methods utilized to address the research objectives and accomplish the research aim.

Table 3.1: Summary of data collection and analysis methods.

Research Objective	Specific methods to collect data			Analysis methods
	Extensive literature review	Questionnaire survey	Case study	
To analyze and model the challenges and the benefits of retrofitting existing residential buildings for NZC	✓	✓		The mean score ranking method and PLS-SEM
To identify and model the available retrofitting measures to reduce the carbon emissions in existing residential buildings	✓	✓		Friedman test, PLS-SEM
To analyze the social, environmental, and economic sustainability changes due to retrofitting	✓		✓	Energy simulation and sustainability analysis

To develop a model to select optimal retrofit strategies for the NZC retrofitting of existing residential buildings	✓	✓	Energy simulation and multi-objective optimization

3.3 Comprehensive Literature Review

A literature review is a data collection methodology that is employed by researchers to give an outline of the research area through the prevailing literature sources within the particular research domain (Kothari, 2004). Further, the literature review serves to extract and synthesize key factors, issues, findings, and research methods relevant to the study (Rudestam & Newton, 2007). In this context, the current study initiated the research process by delving into scholarly works such as journal articles, conference proceedings, book chapters, doctoral dissertations, and online resources. This preliminary step was essential for recognizing the significance of the research within the realm of building retrofitting to achieve NZC. Furthermore, the literature review laid the foundation for pinpointing research gaps, building upon previous studies, and establishing the framework for achieving the study's aims and objectives while addressing research problems.

The literature review was conducted with the objectives: (1) to understand the prevailing theoretical framework and identify research problems; (2) to identify the benefits of building NZC retrofitting; (3) to identify challenges for building NZC retrofitting; (4) to identify measures to retrofit the existing buildings to achieve NZC; (5) to analyze the sustainability concepts considered in building retrofitting; (6) to identify the decision-making approaches developed to decide optimal retrofit strategies in residential building NZC retrofitting; (7) to facilitate the formation of questionnaire to collect data; and (8) to determine the methodologies to be employed in the study. A systematic review has the ability to discover limitations in existing research and provide novel structures to place fresh research endeavors effectively (Arisekola & Madson, 2023). Therefore, this study adopted a qualitative review method by following the systematic approach. To improve the study's quality and ensure adequacy, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method (Fleming et al., 2014) was employed in this study instead of selecting random literature. Hence, it supported the recognition of the research gap and potential upcoming research areas.

Scopus was selected because it is a well-established journal database (Chadegani et al., 2013); has a faster indexing process, thus enhancing the chance of obtaining more recent articles (Meho & Rogers, 2008); and covers a greater number of scientific articles than other databases, such as the Web of Science (Zhao et al., 2019). Keywords were selected for data acquisition based on related studies (Capeluto, 2019; Ohene et al., 2022b) and represented retrofitting existing residential buildings to NZC (refer to Table 3.2). Keywords were connected using Boolean operators, with similar keywords linked using the "OR" operator, while "AND" was used to combine categories of keywords. The literature search used "TITLE-ABS-KEY". Journal articles are more influential and credible for this type of research (Santos et al., 2017) while collecting all document types creates data imbalance, making data analysis and discussion difficult and costly (Hosseini et al., 2018). Hence, the search was limited to articles under the document type without any limitation on the publication period. Articles not published in English and those found with unrelated subject areas (such as chemistry and chemical engineering) were removed since they were beyond the study's scope.

Table 3.2: Literature search keywords.

Aspects	Keywords
Retrofitting	"retrofit*", "renovat*", "refurbish*", "replac*", "rebuild, "reconstruct*", "modif*", "sustainable building retrofit", "sustainable building upgrade", "recommission*", "sustainable building renovation"
NZC	"net-zero carbon", "net-zero emissions", "net-zero energy", "net zero carbon", "net zero emissions", "net zero energy", "zero carbon", "zero emissions", "zero energy", "low carbon", "low energy", "nearly zero emissions", "nearly zero energy", "carbon neutral", "zero net energy", "zero net emissions", "carbon positive", "NZCB", NCEB", "NZC", "NZE", "ZEB", "ZCB", "NZEB", "LCB", "climate neutral*"
Optimization	"optimal", "optimize", "optimise", "optimization", "optimisation"

Existing residential buildings	“hous*”, “home”, “existing building”, “existing buildings”

The findings of the literature review from the search string developed combining keywords related to retrofitting, NZC, and existing residential buildings are illustrated in sections 2.2 and 2.3 of Chapter 2, while 2.4 represents the findings of the literature review conducted using the search string developed by combining all the keywords in Table 3.2. The primary aim of Chapter 2 is to enhance comprehension of building retrofitting towards NZC and provide insights into the associated benefits, challenges, measures, sustainable considerations, and optimal decision-making approaches for building retrofitting to meet NZC.

3.4 Questionnaire Survey

A questionnaire survey is a prevalent data collection methodology employed in research studies to evaluate the relationship between opinions and the perceptions of a large group of people (Pranas et al., 2018). Even though a questionnaire survey is a cost-effective method to collect data from a wide range of people, it has a risk of having a low response rate compared to the distribution rate (Akadiri, 2011). However, it still provides a fantastic chance for researchers to investigate a vast variety of problems if actions are applied to achieve a representative and appropriate sample (Akadiri, 2011). Therefore, the questionnaire survey is one of the most popular data-gathering methods employed by researchers in the construction management domain (Abdulai et al., 2024; Adabre et al., 2021; Darko et al., 2018). As mentioned earlier, this study employed a questionnaire survey as one of its main methods for collecting data.

This study employed two questionnaire surveys that targeted two groups of respondents. However, both questionnaires were created using the factors revealed throughout the comprehensive literature review. Building occupants and experts in the field of residential building NZC retrofitting were the study's target respondents, as detailed in the next section. The questionnaires were administered in this study to:

(with building occupants)

i. identify the significant benefits of residential building NZC retrofitting in Hong Kong and evaluate their interrelationships.
ii. identify the significant challenges for residential building NZC retrofitting in Hong Kong and evaluate their interrelationships.

(with experts)

iii. identify the suitable measures to retrofit the existing residential buildings in Hong Kong to NZC.

3.4.1 Target Respondents

There are numerous stakeholders engaged in the process of retrofitting residential buildings. Among them, building occupants are the primary stakeholders impacted by the building's NZC retrofitting (Sleiman et al., 2024). Further, building occupants' perspectives have been largely ignored by the existing research studies on residential building NZC retrofitting. Moreover, Weerasinghe et al. (2024) detailed that focusing on building occupants will yield experiential engagement of tangible benefits and challenges through actual implications. Therefore, incorporating building occupants' viewpoints is imperative in effectively understanding the challenges and benefits of residential building NZC retrofitting. Hence, this study selected building occupants as the target respondents to identify the significant benefits and challenges of residential building NZC retrofitting.

The study needed to identify the appropriate measures that can be used to retrofit the existing residential buildings toward NZC by employing a questionnaire survey. However, building occupants have comparatively less knowledge and understanding about the performance of different retrofit measures. Therefore, the study targeted the experts in the domain of residential building NZC retrofitting as the respondents for the questionnaire due to their knowledge and experience with retrofit measures.

Accordingly, the study conducted two questionnaire surveys with building occupants and domain experts. The next section describes how the questionnaires for the two target respondents were developed.

3.4.2 Questionnaire Development

3.4.2.1 Questionnaire for Building Occupants

The questionnaire had seven main sections. The first section was used to describe the research, including the aim and objectives. Confirmation of data confidentiality and contact details also were included in the first section. The definitions of key specific terms were included in the second section. The third section was designed to collect background details of the respondents, including their relationships to the building, the age of the building that they lived in, their living experience in Hong Kong, and their awareness about the residential building NZC retrofitting. In the fourth section, respondents were asked to rank various types of retrofitting measures based on their preferences, with a rating of "1" assigned to the most preferred measure. In the fifth and sixth sections, respondents were asked to assess the benefits and challenges of residential building NZC retrofitting. Within the seventh section, respondents were asked to assess building retrofitting methods to measure the residential building NZC retrofitting since it was necessary for the PLS-SEM. The factors in the fifth to seventh sections were considered as the measurement items for the PLS-SEM. All the terms related to the PLS-SEM and the process of modeling are explained in section 3.5.5. A questionnaire sample is included in Appendix A to facilitate a better understanding of the survey.

3.4.2.2 Questionnaire for Experts

This questionnaire consisted of four main sections. Similar to the questionnaire with building occupants, the first section was used to describe the aim and objectives of the research and to include the contact details. The second section was separated for the background details of the respondents, including their profession, working experience, and awareness of residential building NZC retrofitting. The third section was designed for the residential building retrofitting measures, including building envelope upgrades, energy system upgrades, and renewable energy upgrades. In this section, respondents were asked to assess the importance of those measures in achieving NZC residential buildings. In order to measure residential building NZC retrofitting during PLS-SEM, statements describing its benefits were included in section four and respondents were asked to assess them. All the factors included in sections three and four are used as measurement items for PLS-SEM as described in Chapter 6. A sample questionnaire is included in Appendix B to facilitate a better understanding of the survey.

3.4.3 Rating Scales

There are numerous rating scales such as five-point, seven-point, and nine-point rating scales, which can be used to collect opinions from people. However, in the construction management research domain, the five-point Likert scale has been widely used (Abdulai et al., 2024; Adabre et al., 2021; Darko et al., 2018). In addition, the five-point Likert scale is a convenient approach for respondents to express their opinions, and it has been recommended as a method of generating definite findings (Darko et al., 2018). Accordingly, this study assessed the components in the questionnaire survey using the five-point Likert scale, which is simple to comprehend and utilize. Table 3.3 depicts the five-point Likert scales used in different sections of the questionnaires.

Table 3.3: Likert scales used for the questionnaire surveys.

Score	Used term	
1	Strongly disagree[a]	Not important[b]
2	Disagree[a]	Less important[b]
3	Neutral[a]	Neutral[b]
4	Agree[a]	Important[b]
5	Strongly agree[a]	Very important[b]

Note: [a] The five-point Likert scale used in the questionnaire with building occupants, and the fourth section of the questionnaire used for experts; [b] The five-point Likert scale in the third section of the questionnaire used for experts.

3.4.4 Pilot Survey and Distribution of the Questionnaire

3.4.4.1 Pilot Survey

A pilot survey needs to be conducted by a small sample of respondents to assess whether the questionnaire is easy to answer, intelligible, and unambiguous (Nation, 1997). Hence, after developing the questionnaire surveys for two targeted respondents based on the findings of the literature, the questionnaires were piloted before being distributed.

For the questionnaire developed focusing on building occupants, two pilot surveys were conducted. Initially, a survey involving 5 academics with knowledge of NZC retrofitting was conducted to gauge the questionnaire's comprehensiveness, relevance, and use of appropriate technical terms. Subsequently, a survey encompassing 10 building occupants representing diverse cultural backgrounds in Hong Kong was conducted to assess the questionnaire's clarity, ease of completion, and absence of ambiguity. Among the 15 participants surveyed, 46.6% reported having resided in Hong Kong for 4-5 years, while 26.7% had lived in the region for 2-3 years (Table 3.4). The remaining 26.7% had over 5 years of living experience in Hong Kong. Regarding their awareness of NZC retrofitting, a majority of participants (40%) indicated a moderate level of awareness. Additionally, 33.3% reported being extremely aware, while the remaining 26.7% demonstrated somewhat limited awareness (Table 3.4). Accordingly, these findings support the validity and the effectiveness of the pilot survey by confirming a reasonable distribution of experience and awareness levels among participants.

Table 3.4: Details of the participants in the pilot survey (for the questionnaire distributed among building occupants).

Criteria	Frequency of response	Percentage of response
Category		
Building occupants	10	66.7
Academics	05	33.3
Living experience in Hong Kong		
2-3 years	4	26.7
4-5 years	7	46.6
>5 years	4	26.7
Level of awareness about the NZC retrofitting		
Somewhat aware	04	26.7
Moderately aware	06	40.0
Extremely aware	05	33.3

Feedback from the first survey prompted suggestions for modifications in the background information section and the incorporation of a definition for residential building NZC retrofitting. In addition, feedback from the second survey validated the readiness of the questionnaire for distribution. Accordingly, the questionnaire was modified based on the feedback received to prepare the final questionnaire for distribution.

For the questionnaire developed focusing on experts, a pilot survey was conducted involving 15 experts, comprising academics and professionals from the construction industry, who possessed a comprehensive knowledge of NZC retrofitting in buildings (Table 3.5). Professional distribution of participants indicated that academics accounted for 46.67% of the participants, followed by engineers (33.33%), consultants (13.3%), and a project manager (6.67%). Regarding work experience, the majority of participants (53.33%) reported having 6-10 years of experience in the construction sector, while 33.33% were under 1-5 years and 13.34% were under 11-15 years of experience. Importantly, all participants demonstrated awareness of NZC retrofitting. Specifically, 53.33% reported being moderately aware, 40.00% were extremely aware, and 6.67% were somewhat aware. These findings validate the appropriateness of the selected sample for the pilot survey.

Table 3.5: Details of the participants in the pilot survey (for the questionnaire distributed among experts).

Criteria	Frequency of response	Percentage of response
Profession		
Consultant	02	13.33
Academics	07	46.67
Project Manager	01	06.67
Engineer	05	33.33
Working experience		
1-5 years	05	33.33
6-10 years	08	53.33
11-15years	02	13.34
Level of awareness about the NZC retrofitting		
Somewhat aware	01	06.67
Moderately aware	08	53.33
Extremely aware	06	40.00

The experts gave valuable feedback on the questionnaire. They were asked to make additions as well as omissions to the questionnaire. For instance, experts asked to add “upgrade floor finishes and coverings” as a measure under floor finishes and “use of wind assisted ventilation system” as a measure under wind energy while they asked to omit factors such as “provide better building appearance”, “attractive return on investments”, “enhance the quality of life for occupants”, “reduce vulnerability to fluctuating prices”, and “creating new job opportunities” since those factors are repeating the meaning of available factors. The expert’s advice on the questionnaire was to shorten it, noting that the experts’ hectic schedules may cause delays in responding to the questionnaire if it is deemed too long. However, based on the feedback received through the pilot survey, the questionnaire was modified to prepare the final questionnaire for distribution.

3.4.4.2 Questionnaire Distribution

The building occupants in Hong Kong and the experts in Hong Kong with knowledge and understanding of residential building NZC retrofitting were the populations for the two developed questionnaires of this study. In respondent sampling, two primary types are commonly employed: “probability sampling” and “non-probability sampling” (Pandey & Pandey, 2021). “Probability sampling” entails methodologically choosing samples from a population, ensuring that every individual has a chance of selection (Adabre et al., 2021). In contrast, “non-probability sampling” entails picking units from the entire population utilizing subjective, quick, transparent, and inexpensive approaches (Mishra & Alok, 2017). As there was no sampling frame, this study followed a nonprobability sampling method (Zhao et al., 2015). A representative sample can be achieved by utilizing the nonprobability sampling method (Adabre et al., 2021). However, it is suitable in cases where a random sampling technique is not feasible for selecting respondents from the population, and instead, respondents are chosen based on their voluntary willingness to take part in the research study (Wilkins, 2011). In studies related to construction management, snowball sampling has been frequently utilized (Abdulai et al., 2024; Darko et al., 2018) given its ability to acquire and connect with respondents through online platforms or referrals. Therefore, this study adopted a non-probability snowball sampling method to recruit respondents to the questionnaire.

Distribution of questionnaire among building occupants

Hong Kong government telephone directory and 28 Hse App (Leung, 2005) were used to find the details of Hong Kong building occupants since those had access to the majority of building occupant’s details. In addition, respondents were asked to share information about other building occupants. However, the questionnaire link was individually emailed and published on WhatsApp (Acton & Kokum, 2009) and WeChat (WeChat, 2011) to collect the responses from the building occupants. Finally, 123 completed questionnaires were received, representing a 30.75% response rate.

Distribution of questionnaires among experts

During the distribution process, different organizations such as the Hong Kong Building Department and Green Building Council, that serve the target population were identified. Then, emails were used to collect data from diverse respondents across these organizations. Further, identified respondents were requested to share information about other relevant participants who could contribute to the study. Ultimately, within a six-month timeframe, a total of 52 completed responses were obtained, indicating a 29.7% rate of response.

The sample size of the two surveys has adhered to the recommended guideline in the central limit theorem, which should exceed 30 (Ott & Longnecker, 2016). Further sample sizes 123 and 52 are sufficient for the analysis when compared with the previous construction management studies, which used sample sizes of 43 (Darko et al., 2018) and 47 (Adabre et al., 2022). The details of the respondents are described in section 3.6.

3.5 Data Analysis Methods Used for the Questionnaire Survey

The data gathered from the questionnaire surveys underwent analysis through various statistical methods detailed in the subsequent sections.

3.5.1 Reliability of Data – Cronbach's Alpha

Cronbach's Alpha is a widely used method to measure the reliability of data. This metric gauges the consistency of a rating scale by examining the average correlation or internal coherence among the variables evaluated using the scale (Santos, 1999). Typically, a Cronbach's alpha coefficient value equal to or greater than 0.70 signifies that the scale is reliable (Nunnally, 1978). Accordingly, before starting the data analysis, the reliability of the five-point rating scale employed to collect survey responses was assessed using Cronbach's alpha coefficient. This study used both the Statistical Package for Social Science (SPSS) and PLS-SEM to calculate Cronbach's alpha value, and the results are discussed in Chapters 4, 5, and 6.

3.5.2 Data normality test – Shapiro-Wilk test

The Shapiro-Wilk test is used to determine the normality of data distributions (Ferretti et al., 2017). Therefore, this study employed the Shapiro-Wilk test to evaluate the normality of data, as it is crucial to establish the normality of data before employing other statistical methods (Kim, 2015). A standard significance level of 0.05 was applied during the test, and the null hypothesis of this test assumes that the data follows a normal distribution. If the calculated *p*-value falls below this threshold, the null hypothesis is rejected, indicating that the data deviates from normality. In this study, all *p*-values from the Shapiro-Wilk test were below 0.05, showing non-normality in the data. This result was expected because data from small samples often do not follow a normal distribution (Hwang et al., 2018; Shan et al., 2017).

3.5.3 Friedman Test

The Friedman test is the most popular statistical method used to assess the significance differences between more than two groups towards one target variable (Kim, 2017; Puteh & Azman Ong, 2017). Friedman tests the null hypothesis, which states that *n* related variables are from the same population. In each case, the n variables are ranked from 1 to *n,* and the test calculated the statistics based on these rankings. Therefore, the Friedman test was employed in this study to analyze the ranked data according to the preferences of building occupants. SPSS was employed in this study to conduct the Friedman Test. The results of the Friedman test are described in Chapter 6.

3.5.4 Mean Score Ranking Method

The mean score ranking method is a commonly utilized statistical technique for organizing respondents' perspectives in a descending manner based on their importance or criticality (Chan & Adabre, 2019). This study used this method to rank the benefits, challenges, and measures of residential building NZC retrofitting. When multiple factors shared identical mean scores, the standard deviation (SD) was utilized. Subsequently, the factor with the lowest SD was assigned the highest rank (Darko & Chan, 2018). A smaller SD indicates that the discrepancies in responses were not significantly large, thereby implying that the average is more likely to be representative of the majority (Staplehurst & Ragsdell, 2010). In addition, a one-sample t-test was conducted to evaluate the statistical significance of the factors. The resulting *p*-values below 0.05 indicate that all the factors are significantly important.

3.5.5 Modeling: PLS-SEM

Structural Equation Modeling (SEM) is a multivariable statistical assessment approach that effectively addresses errors encountered during data analysis (Haenlein & Kaplan, 2004). It is used to statistically analyze the correlation between multiple variables (Hair et al., 2021). This study used SEM to evaluate the influence of benefits, challenges, and measures on the residential building NZC retrofitting. SEM comprises two categories of variables: observable variables (also known as measurement items) and latent variables (also known as constructs). Directly measurable variables are observable, while latent variables are inferred from these measurement items due to their inability to be directly measured (Jayasena et al., 2024). A key benefit of SEM is its ability to evaluate direct as well as indirect connections between one or more independent variables and/or dependent variables (Byrne, 2013), surpassing the capabilities of traditional statistical data analyses (Ozorhon & Oral, 2017). Therefore, SEM was selected for data analysis of this study.

There are two fundamental approaches to conducting SEM: (1) covariance-based SEM (CB-SEM) and (2) variance-based PLS-SEM. The CB-SEM is generally used for normally distributed data with a large sample size (about 200) to ensure accurate model assessment (Aibinu & Al-Lawati, 2010). Conversely, PLS-SEM can effectively handle small sample sizes, even in cases where the normality assumption of the data is questionable (Hair et al., 2021). Therefore, in numerous research studies within the field of construction management, PLS-SEM has been favored over CB-SEM. For instance, PLS-SEM was used to evaluate the interaction among collaborating actions and organizational justice in the construction sector by

Aibinu et al. (2011) using responses from 41 contractors. A sample size of 35 experts was used in a PLS-SEM analysis conducted by Zhao and Singhaputtangkul (2016) to assess the effects of Chinese construction organization properties on organization risk management. Furthermore, Darko et al. (2018) employed PLS-SEM to assess the impacts of drivers, barriers, and strategies on green building adoption in developing nations using responses from 43 experts. According to Hair et al. (2021), to use PLS-SEM, the anticipated number of samples should exceed 10 times the maximum arrows directed toward a construct (variables that are directly measured). Corresponding to the hypothetical models for benefits, challenges, and measures (Figure 4.2, Figure 5.2, and Figure 6.2), the greatest number of arrows pointed at the construct of residential building NZC is 3 (30 < 123), 6 (60 < 123), and 5 (50 < 52), respectively. Hence, the sample sizes of the two questionnaire surveys are greater than the requirement of PLS-SEM. Given these considerations, PLS-SEM is regarded as suitable for this study to assess the proposed hypotheses and validate the hypothetical models, using SmartPLS 4 software. PLS-SEM was applied in this study to:

i. model the influence of numerous challenges for retrofitting on residential building NZC retrofitting;
ii. model the influence of numerous benefits of retrofitting on residential building NZC retrofitting; and
iii. model the appropriateness of numerous retrofitting measures on residential building NZC retrofitting.

Two types of models are estimated in PLS-SEM: (1) measurement model and (2) structural model. The measurement model assesses the connections between a construct and its corresponding measurement items while the structural model illustrates the linkage among different constructs (Hair et al., 2021). Accordingly, measurement model evaluation is done before the structural model evaluation since it ensures the accuracy of the constructs that are used to investigate the hypotheses made in the structural model (Hair et al., 2021). Therefore, after specifying the measurement items and the constructs, the reliability and the validity of the relationship between measurement items and the constructs are evaluated in the measurement model.

Reliability concerns the degree to which the measurement of constructs accurately reflects the true scores using a multi-item scale while accounting for measurement error (Abdulai et al., 2024). Cronbach's alpha and composite reliability scores are used to assess the internal consistency reliability of the measurements at every construct. Even these two metrics have similar interpretations, Cronbach's alpha should be 0.7 or more while the composite reliability score should exceed 0.7 to confirm the reliability (Hair et al., 2021). After ensuring reliability, validity is confirmed through convergent and discriminant validity measures. Convergent validity is measured by evaluating the factor loadings and average variance extracted (AVE). Factor loadings reflect the bivariate relationships across measurement items and their related constructs, acting as the method via which the measurement items attach to the constructs (Hair et al., 2014). Each measurement item should exhibit 0.5 or above factor loading and AVE to satisfy the convergent validity (Abdulai et al., 2024). AVE can be explained as the mean squared loading of measurement items (Hair et al., 2014).

Discriminant validity examines whether a construct assesses its desired attributes distinctly from other constructs. This study employed Fornell and Larcker, HTMT, and cross-loading for assessing discriminant validity. Corresponding to Fornell and Larcker (1981) construct's shared variance with its measurement items should be above the shared variance of it with other constructs. Therefore, AVE for every construct should be greater than its largest squared correlation with the other ones. To evaluate the HTMT ratio, it is necessary to compare the correlations with a predefined threshold, which is typically set at 0.90 (Adabre et al., 2022). In order to meet the conditions, all correlations must be below the established threshold. With regard to cross-loading, the loading of every measurement on its respective construct should be higher than its loadings on others (Chin, 1998).

The structural model analysis was conducted to assess the importance of the hypotheses. Once the measurement model's reliability and validity are confirmed, it is needed to assess the path coefficients within the structural model to test hypotheses. Path coefficients depict the connections between constructs (Hair et al., 2021). Therefore, the bootstrapping technique which is a flexible method of assessing the impacts of hypotheses in various types of data distributions (Jack et al., 2001), was employed in this study to test the hypotheses. This study applied 5000 bootstrap subsamples, as suggested by Hair et al. (2021), which corresponded to the total number of replies. Utilizing an excessive number of bootstrap subsamples is critical for guaranteeing result consistency. As per Astrachan et al. (2014), significant t-values for a two-tailed test were 1.65, 1.96, and 2.58 with 0.1, 0.05, and 0.01 significance levels, respectively. The outcomes of the PLS-SEM analysis are discussed in Chapters 4, 5, and 6.

3.6 Background Details of Respondents

As detailed in the above sections, this study conducted two questionnaire surveys, targeting building occupants and experts as respondents. The respondents' background details in each survey are detailed in the sections below.

3.6.1 Survey with Building Occupants

The background details of the respondents are illustrated in Table 3.6. Among building occupants, 63.4% of respondents were building owners, while 36.6% were tenants. In terms of living experience in Hong Kong, 68.3% had over 5 years of residency, with only 12.2% having

2-3 years, 10.6% with less than a year, and 8.9% with 4-5 years. Regarding the age of the buildings they resided in, the majority (34.1%) were over 40 years old, followed by 27.6% for 31-40 years, 9.8% for 21-30 years, 7.3% for 11-20 years, 6.5% under 10 years, and 14.6% were uncertain about the age. This suggests a predominance of older buildings in Hong Kong, highlighting the necessity for NZC retrofitting. With regard to the level of awareness about NZC retrofitting, 32.5% of respondents were moderately aware, 26.8% were somewhat aware, 17.4% were slightly aware, 11.4% were extremely aware, and 11.4% were unaware. The data provided by respondents on their awareness of NZC retrofitting contributed to enhancing the credibility of the study findings.

Table 3.6: Details of the respondents (building occupants).

Criteria	Frequency of response	Percentage of response
Relationship with the building		
Owner	78	63.4
Tenant	45	36.6
Living experience in Hong Kong		
0-1 years	13	10.6
2-3 years	15	12.2
4-6 years	11	8.9
>5 years	84	68.3
Age of the living building		
0-10 years old	8	6.5
11-20 years old	9	7.3
21-30 years old	12	9.8
31-40 years old	34	27.6
>40 years old	42	34.1
Don't know	18	14.6
Level of awareness about the NZC retrofitting		
Not at all aware	14	11.4
Slightly aware	22	17.9
Somewhat aware	33	26.8
Moderately aware	40	32.5
Extremely aware	14	11.4

3.6.2 Survey with Experts

The background details of the respondents are illustrated in Table 3.7. Professional distribution of respondents indicated that engineers accounted for 34.62% of the respondents, followed by architects (21.15%), project managers (19.23%), researchers (11.54%), consultants (7.69%), and work inspectors (5.77%). Regarding work experience, the majority of respondents (40.38%)

reported having more than 20 years of experience in the construction sector while 25% were under 6-10 years, 17.31% were under 16-20 years, 11.54% were under 11-15 years, and 5.77% were under 1-5 years of experience categories. Importantly, all respondents demonstrated awareness of NZC retrofitting. Specifically, 40.38% reported being moderately aware, 25% were extremely aware, 19.23% were somewhat aware, and 15.38% were slightly aware. These results also validated that the participants had the essential knowledge, skills, and credentials to contribute significantly to the study's scope.

Table 3.7: Details of the respondents (experts).

Criteria	Frequency of response	Percentage of response
Profession		
Engineer	18	34.62
Architect	11	21.15
Project Manager	10	19.23
Researchers	6	11.54
Consultant	4	7.69
Work Inspectors	3	5.77
Working experience		
1-5 years	3	5.77
6-10 years	13	25.00
11-15years	6	11.54
16-20 years	9	17.31
Over 20 years	21	40.38
Level of awareness about the NZC retrofitting		
Slightly aware	8	15.38
Somewhat aware	10	19.23
Moderately aware	21	40.38
Extremely aware	13	25.00

3.7 Sustainability Analysis of the Case Study

A sustainability assessment of a specific case study was executed through simulation and sustainability calculations to assess the effectiveness of a residential building post-retrofitting. After the simulation process, an optimization analysis was carried out to ascertain the most effective retrofit strategies emphasizing social, environmental, and economic sustainability factors. The subsequent sections describe the case study, simulation methodologies, mathematical equations, and optimization algorithms employed to fulfill the study's objectives.

3.7.1 Description of the Case Study

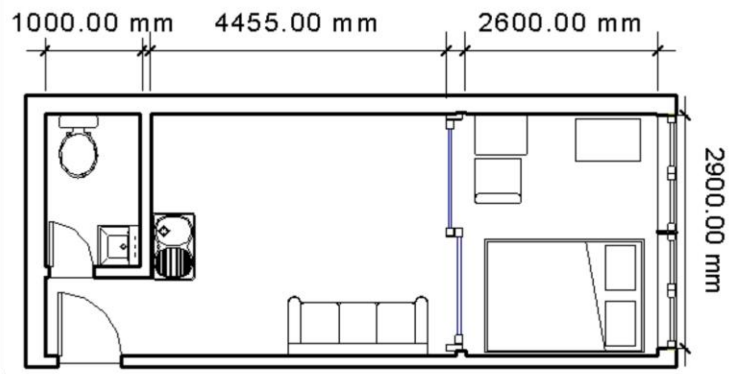
A case study is a research approach that offers a comprehensive insight into a phenomenon by utilizing various data sources (Hancock et al., 2021). In assessment scenarios, case studies are frequently employed to record and scrutinize implementation procedures (Paleyes et al., 2022). In this study, a case study was utilized to evaluate the energy and carbon performances of retrofit strategies along with the average percentage of occupant dissatisfaction. Further, the case study was used to implement and validate the multi-objective optimization model. According to Yin (2009), case studies can be carried out as a single case study or multiple case studies. Additionally, as per the aforementioned author, a single case study is warranted for exceptional circumstances, while multiple case studies can be conducted when cases are available. Accordingly, most of the researchers have employed one case study to decide optimal retrofit strategies in reducing carbon emissions and energy consumption (Amani et al., 2024; Salata et al., 2020). Therefore, one case study was conducted for this study, considering time constraints and limited data availability.

The emerging issue within the developed countries to achieve the NZC target is the massive stock of existing buildings. Moreover, as detailed in section 1.4.2, it is necessary to consider the NZC retrofitting of residential buildings in Hong Kong due to their higher contribution to carbon emissions. Most of the residential buildings in Hong Kong are multi-unit residential buildings consisting of both private and public buildings (GovHK, 2020). However, retrofitting residential buildings in Hong Kong is a difficult task due to the multiple ownership of different residential units within the same building (IENV, 2023). As per the NZC building framework definition, the operational energy boundary can be established as either an "individual dwelling/tenant area in a multi-unit building" or a "whole building" itself (UKGBC, 2019).

Accordingly, considering these factors, the study selected an individual residential unit from a multi-unit residential building as the case study.

Focusing on the data availability to conduct the simulation, the study selected a two-person residential unit in the Seng Ming Court residential building, North Point, Hong Kong as the case study. The building was constructed in 1967 and comprises 13 floors and 23 residential units, with the selected unit situated on the 12th floor. The unit was comprised of distinct areas such as a bedroom, living area, kitchen, and bathroom, spanning a total area of 23.94m^2. The selected residential building was located between a residential building (left side) and a commercial building (right side), which are taller than the selected case. The presence of several nearby building types further adds to the difficulty of NZC retrofitting. Figure 3.1 depicts the location of the selected case study building, which clearly demonstrates the difficulties associated with the nature of high-rise and urbanization for NZC retrofitting of residential buildings in Hong Kong

Actual location of the case study building



Plan view of the selected case

Figure 3.1: Details of the selected case.
Source: Author’s own development.

3.7.2 Building Simulation Tool

Building simulation has emerged as a widely embraced and reliable methodology utilized by both academic and industry practitioners to inform decisions regarding the operational efficiency of buildings. The utilization of building simulation has demonstrated its efficacy in facilitating research within the built environment, offering fewer chances for human error and expedited outcomes, supported by a variety of available software packages (Abu-Hijleh et al., 2017). Researchers have used software such as eQUEST (Lamichhane et al., 2024), EnergyPlus (Porsani et al., 2023), DOE2 (Dhakal et al., 2004) and Integrated Environmental Solutions Virtual Environment (IESVE) to evaluate the energy and thermal performance of buildings (Chang et al., 2024). Crawley et al. (2008) highlighted the IESVE’s comprehensive evaluation features, including building envelope, thermal comfort, and solar influences, in a comparative study of 20 simulation software tools. Moreover, IESVE has the capacity to assess energy consumption, carbon emissions, and occupant dissatisfaction (IES, 2023), which are pivotal for evaluating the environmental and social impacts of residential building NZC retrofitting. Therefore, IESVE was selected as the simulation tool for this study. The process followed in building simulation is discussed in Chapter 7.

3.7.3 Sustainability Analysis

The following equations and parameters were used to evaluate the social, environmental, and economic sustainability while retrofitting residential buildings to NZC.

3.7.3.1 Social Sustainability

The direct impact on building occupants is an important factor to consider when retrofitting buildings. The predicted percentage of dissatisfaction (PPD) is a widely used parameter to assess occupant's dissatisfaction with the retrofitting measures used, particularly in terms of temperature conditions inside the building (Guenther, 2024). This study also used PPD as the metric to assess social sustainability with the residential building NZC retrofitting. According to ASHRAE (2023) recommendations, keeping the PPD below 20% is critical for occupant comfort. The PPD values reflecting occupant dissatisfaction, as obtained directly from the VistaPro Comfort analysis tool within the IESVE platform, were used in this study to assess the social sustainability dimension of retrofitting residential buildings to NZC.

3.7.3.2 Economic sustainability

Economic sustainability is an essential factor in accepting residential building retrofitting. It was expected that the energy savings gained quickly after the building retrofitting would equal or exceed the initial investment for retrofitting. For the profitability assessment, a streamlined life cycle cost (LCC) approach was used, which took into account the initial investment costs of obtaining retrofitting materials, as well as energy savings (Dauletbek & Zhou, 2022). When performing LCC analysis for economic evaluation, the choice between nominal costs, accounting for inflation rates, and real costs, reflecting present item values, is pivotal (Bull, 2003). To reduce uncertainty associated with inflation forecasts, it is recommended to include real costs in LCC calculations when evaluating various investment options (Dwaikat & Ali, 2018). Given the study's emphasis on profitable investments, a simplified LCC analysis utilizing real costs without factoring in inflation rates was adopted, aligning with the methodology used in the study conducted by Dauletbek and Zhou (2022).

Market survey, which is serving as a fundamental unit of market analysis for a specific product or service, encompassing investigation of pricing (Bhat, 2025), was employed in this study to determine the cost of retrofit materials. Dauletbek and Zhou (2022) used a three-month market survey to determine the real cost of construction materials before doing a simplified LCC analysis. Following that, this study monitored online marketing platforms such as Alibaba, Fortress, Wealth Bridge Co. Ltd, and RS components for three months (August-October, 2024) to determine the cost of retrofit materials. Since the cost of materials did not significantly change during the three-month period, those prices were used as the initial cost for retrofit materials. The study's major goal was to determine whether measures used to achieve NZC would result in cost savings through energy efficiency increases during the building's lifetime. Accordingly, the following equations, 1 and 3 (Dauletbek & Zhou, 2022; He et al., 2021b), were used to calculate economic sustainability with the NZC retrofitting, considering the annual and lifetime energy performance of the building after retrofitting.

Considering the post-retrofit lifetime performances, lifetime economic profitability (EP) was calculated as,

$$EP = (E_{save} \times EC) - \sum IC_i \quad (1)$$

Where,

$$E_{save} = (E_{base} - E_{retrofitted}) \times A \times LT \quad (2)$$

Considering the post-retrofit annual performances, annual EP was calculated as,

$$EP = (E_{save} \times EC) - \left(\frac{\sum IC_i}{LT}\right) \quad (3)$$

Where,

$$E_{save} = (E_{base} - E_{retrofitted}) \times A \quad (4)$$

In these equations,

EC	*= Average energy cost*
IC	*= Initial investment cost for retrofit measures*
i	*= Different retrofit measures in the strategy*
E_{save}	*= Annual/ Lifetime energy saving due to retrofitting*
E_{base}	*= Base case annual energy consumption in* kWh/m^2
$E_{retrofitted}$	*= Annual energy consumption after retrofitting in* kWh/m^2
A	*= Gross floor area of the building*
LT	*= Lifetime of the building*

3.7.3.3 Environmental Sustainability

The study's focus is on eliminating carbon emissions from residential buildings in order to mitigate the effects of climate change. Thus, carbon reduction was used as a metric to assess environmental sustainability in the retrofitting process. Both operational carbon emissions as well as embodied carbon of retrofit materials need to be considered during this process. Accordingly, IESVE, which is employed for simulation, is used to determine the carbon emissions during the pre-retrofitting and post-retrofitting stages. OneClick LCA, a life cycle assessment (LCA) tool, calculates the embodied carbon in building materials, considering parameters such as location, size, and building type (Palugulla, 2024). Hence, this study used OneClick LCA software to calculate the embodied carbon of retrofitting materials. Finally, the following Equations 5 and 6 (UKGBC, 2019) were employed to quantify the carbon reduction resulting from residential building NZC retrofitting as a measure of mitigating environmental impacts.

Considering the post-retrofit lifetime performances, lifetime carbon saving was calculated as,

$$C_{save} = (C_{base} - C_{retrofitted}) \times LT - \sum EC_i \tag{5}$$

Considering the post-retrofit annual performances, annual carbon saving was calculated as,

$$C_{save} = C_{base} - \left(C_{retrofitted} + \left(\frac{\sum EC_i}{LT}\right)\right) \tag{6}$$

In these equations,

C_{save}	= *Carbon saving after retrofitting*
C_{base}	= *Base case annual operational carbon emissions*
$C_{retrofitted}$	= *Annual carbon emissions after retrofitting*
EC	= *Embodied carbon of retrofit measure*
i	= *Different retrofit measures in the strategy*
LT	= *Lifetime of the building*

3.8 Development of the Model to Select Optimal Retrofit Strategies

The model development was formulated through optimization using different algorithms, and Streamlit framework was used to deploy the model as detailed in the sections below.

3.8.1 Optimization

Optimization is a systematic process employed to identify the optimal values or solutions for given problems (Gunantara, 2018). Typically, optimization endeavors to ascertain either minimum or maximum values/solutions by considering one or more objectives. Consequently, the pursuit of optimal solutions for problems characterized by more than one objective is known as multi-objective optimization (MOO) (Gunantara, 2018). However, attaining a singular optimal solution poses challenges within MOO due to the inherent conflicts among objectives (Yao et al., 2023). Consequently, MOO yields a set of optimal solutions, referred to as the “Pareto optimal front” or “Pareto optimal solutions” (Gardi et al., 2016). The Pareto optimal front represents a collection of solutions that are non-dominated, as the enhancements of one objective invariably impact other objective functions (Rahman & Szabó, 2021). In the context of this study, the attempt is to identify retrofit strategies that maximize social, environmental, and economic sustainability during residential building NZC retrofitting. Accordingly, this study focuses on addressing a multi-objective issue. Therefore, MOO was employed in this study to determine the optimal retrofit strategies for residential building NZC retrofitting.

After gathering data from simulations, a market survey, and a life cycle assessment of retrofit materials, the data was imported into Jupyter Notebook for optimization. Preceding the commencement of optimization, it was imperative to define the objectives, variables, and constraints.

- Objectives – Represent the central aspect of components within any optimization problem, delineating the quality of a viable solution to the problem (Vasudeva et al., 2022). Determined by whether a problem entails minimization or maximization, objectives set out to be minimized or maximized (H. Liu et al., 2020). Hence, objectives stipulate what requires optimization, whether through minimization or maximization.
- Variables – Represent the adjustable parameters that influence the objectives (H. Liu et al., 2020).
- Constraints – Represent the elements of optimization problems that indicate the limits of restrictions on variables (Vasudeva et al., 2022). Accordingly, variables need to fulfill the conditions made by constraints to find the optimal solutions for the optimization problem.

Furthermore, the determination of the population size and the number of generations is essential. Population size represents the number of potential solutions within a generation, and a higher population size results in a diversity of solutions from the optimization (Eiben & Smit, 2012). The generations are the number of cycles/ iterations that the algorithm goes through to assess the fitness of solutions within the population, and it is repeated until the optimal solutions are achieved (Eiben & Smit, 2012). The following Figure 3.2 illustrates the steps followed in this study in conducting optimization, and Chapter 9 gives a detailed explanation of the multi-objective optimization process followed in this study.

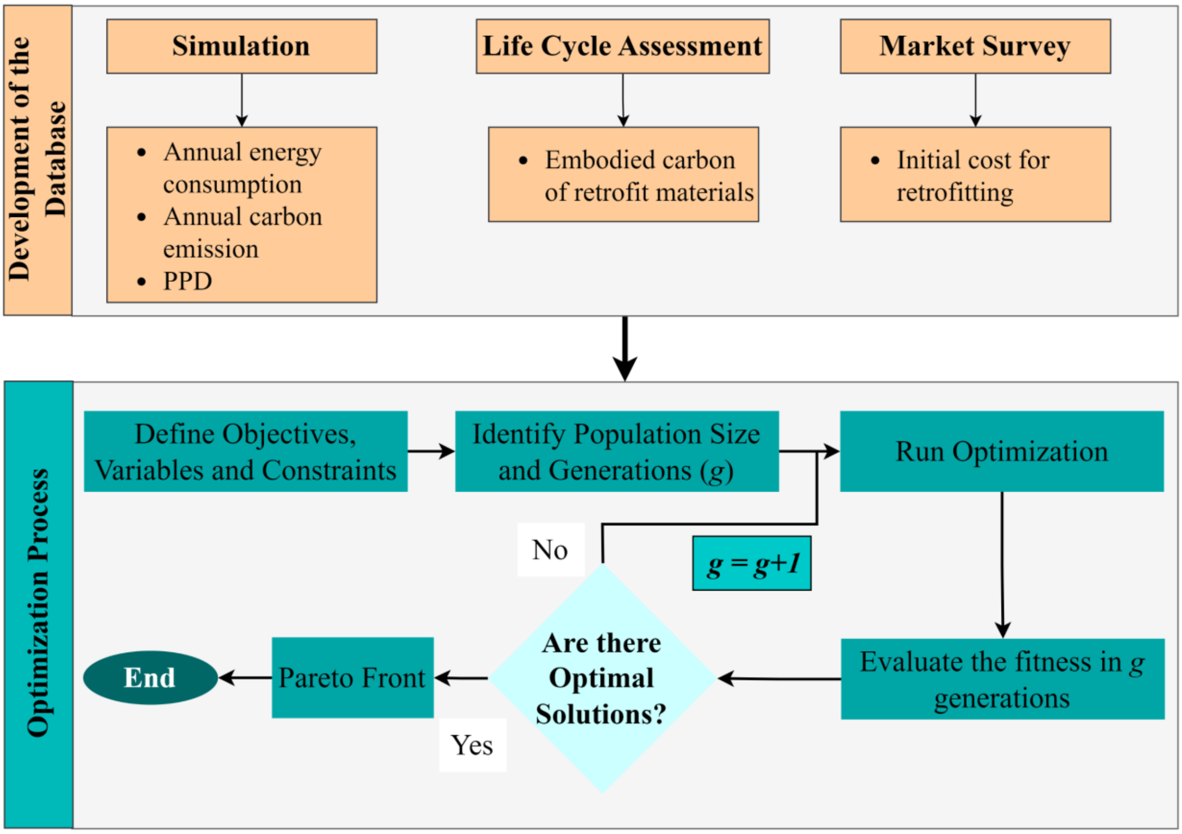


Figure 3.2: Steps followed in optimization.
Source: Author's own development.

3.8.2 Optimization algorithms

Multi-objective evolutionary algorithms (MOEAs) were selected to solve this optimization problem due to their proven effectiveness in handling complex, multi-modal problems with conflicting objectives. Unlike traditional optimization methods that require objective function weighting or hierarchical approaches, MOEAs can simultaneously evolve a population of solutions toward the set of optimal solutions (Pareto optimal front) (Redondo et al., 2017). Evolutionary algorithms encompass a broad category of population-based metaheuristics, with genetic algorithms representing a specific subset that employs genetic operators (crossover, mutation, selection) (Taiwo et al., 2024). This study implemented three advanced MOEAs that have demonstrated superior performance in construction management (Redondo et al., 2017; Taiwo et al., 2024):

Non-dominated Sorting Genetic Algorithm II (NSGA-II) is a well-established genetic algorithm featuring fast non-dominated sorting and crowding distance mechanisms for maintaining solution diversity across the Pareto front (Amani et al., 2024). Similarly, Non-dominated Sorting Genetic Algorithm III (NSGA-III) is an enhanced version of NSGA-II designed for many-objective problems, employing reference point-based selection to improve convergence and diversity in higher-dimensional objective spaces (Behera et al., 2025). Adaptive Grid-based Evolutionary Algorithm (AGE-MOEA) is a grid-based approach that adaptively adjusts search strategies based on solution distribution, providing superior performance in maintaining solution diversity and handling irregular Pareto front geometries (C. Liu et al., 2019). The implementation of three distinct algorithms enables validation of solution quality through algorithmic consensus and provides confidence in the robustness of identified optimal retrofit strategies. This multi-algorithm approach also allows for comparative analysis of algorithmic performance in the specific context of building retrofit optimization.

3.8.2.1 Non-Dominated Sorting Genetic Algorithm II (NSGA II)

Non-dominated sorting genetic algorithm II (NSGA II) is a widely used algorithm in solving multi-objective optimization problems, employed in this study to solve a multi-objective problem. It uses diversity preservation mechanisms and elitism principles in obtaining the Pareto optimal solutions (De Buck et al., 2019). Initially, a parent population is established, from which an offspring population is generated. Subsequently, these populations are merged and categorized through non-dominated sorting. Upon the completion of this sorting process, the creation of a new population commences, starting with the designation of rank 1 for the top non-dominated front (Deb et al., 2002). This progression continues subsequent fronts with the assignment of ranks. In addition, to non-dominated sorting, another method employed is the utilization of crowding distance sorting. The crowding distance serves as a measure of how closely a solution relates to its neighbors, with greater distances indicating enhanced diversity within the Pareto front (Mohanty et al., 2017). The offspring population is derived from the parent population through the utilization of crowded tournament selection, crossover, and mutation operators.

3.8.2.2 Non-Dominated Sorting Genetic Algorithm III (NSGA III)

Non-dominated sorting genetic algorithm III (NSGA III) is utilized for addressing problems with more than two objectives (Seada & Deb, 2015). Since the current study also has three objectives, this was utilized for optimization. NSGA III follows a similar approach to NSGA II in assigning rank 1 to the non-dominated front through non-dominated sorting. However, while NSGA II employed crowding distance to enhance diversity in achieving subsequent goals, NSGA III introduced the utilization of reference points to preserve solution diversity (Chaudhari et al., 2022). In this process, solutions from the given front are projected onto a normalized plane, which is further subdivided into equi-spaced reference points. Each projected solution on the normalized plane is then linked with the nearest reference point. A selection process ensues post-association to ensure that the selected solution set represents a maximum number of reference points (Deb & Jain, 2014).

3.8.2.3 Adaptive Grid-based Evolutionary Algorithm (AGE-MOEA)

The adaptive grid-based evolutionary algorithm (AGE-MOEA) shares similarities with NSGA II, but it employs a revised crowding distance formula. Essentially, AGE-MOEA is an adapted iteration of NSGA II that substitutes the conventional scores allocated to solutions within each non-dominated front. In AGE-MOEA, the traditional crowding distance utilized in NSGA II is substituted with a survival score that integrates both the diversity and proximity of solutions within the given non-dominated front (Panichella, 2019).

3.8.3 Deployment of Multi-Objective Optimization Models

To facilitate practical implementation and accessibility of the developed multi-objective optimization models, the Streamlit framework was employed to deploy them as an interactive web application. Streamlit provides a Python-native approach for rapidly developing and deploying interactive web applications specifically designed for data science and machine learning applications (Mhadbi, 2021). This framework enables users to seamlessly input building and retrofit data while obtaining optimized NZC retrofitting solutions through an intuitive interface. The deployment process involved several critical implementation steps. First, developed optimization models were integrated into the Streamlit application architecture, ensuring seamless data flow from user inputs through the optimization algorithms to result presentation. The application was developed entirely using Python and its associated libraries, leveraging Streamlit's built-in components for user interface elements, data visualization, and interactive widgets. Unlike traditional web development approaches, Streamlit applications do not require separate HTML, CSS, or JavaScript development, as the framework automatically generates these elements from Python code, significantly simplifying the deployment process (Taiwo et al., 2025). The application architecture was designed to handle multiple user sessions simultaneously while maintaining computational efficiency and preventing operational disruptions. More details of the web application can be found in section 9.4.

3.9 Chapter Summary

This chapter describes the methodology used in this study to attain its research objectives. As a result, the chapter discusses both the data collecting and analysis methodologies. The study used a quantitative research approach, with data obtained from questionnaire surveys and a case study. The questionnaires were created after doing a thorough assessment of the literature and were moderated in response to comments from pilot surveys. The questionnaire data was analyzed using mean score ranking, a normality test, and PLS-SEM. Simulation, sustainability analysis, and optimization were adopted for the case study. Building drawing, energy data, and occupant schedules were gathered from the case study to simulate the building to collect data on energy consumption, carbon emissions, and PPD. The Streamlit framework was used to deploy MOO models. The research aims and objectives were reached using a combination of the methodologies indicated in this chapter. The next chapter presents literature review and identifies research gaps.

CHAPTER FOUR[4]

4.0 Analysis and Modeling of the Relationship between the Benefits of Residential Building NZC Retrofitting

4.1 Introduction

The preceding chapters provided an overview of the research, revealing the pertinent literature and research methodology. This chapter's primary objectives encompass identifying the significant benefits associated with retrofitting residential buildings to NZC and formulating a model to represent the relationship between various benefits and the process of residential building NZC retrofitting. These objectives were achieved through a questionnaire survey administered among building occupants in Hong Kong, as outlined in section 3.4. The benefits listed in Table 2.1 were utilized in the questionnaire, with 123 building occupants participating in this survey, and their details were outlined in Table 3.6. Respondents ranked the benefits of residential building NZC retrofitting on a five-point Likert scale, ranging from 1 for "strongly disagree" to 5 for "strongly agree". The collected data underwent analysis using the SPSS package and SmartPLS 4. The outcomes are comprehensively described in this chapter, emphasizing the relationship between benefits and the retrofitting of residential buildings to NZC. These findings underscore the criticality of identifying these pivotal benefits for the successful implementation of residential building NZC retrofitting. Accordingly, this chapter furnishes substantial insights for policymakers, advocates, and industry practitioners interested in promoting and retrofitting residential buildings to NZC.

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[4] This chapter has been partially published in Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2025). Critical benefits in retrofitting residential buildings to net zero carbon. *Smart and Sustainable Built Environment*. 1-25, https://doi.org/10.1108/SASBE-06-2025-0297.

4.2 Identification of Significant Benefits from Residential Building NZC Retrofitting

4.2.1 Statistical Analyses

Prior to data analysis, the reliability of the five-point rating scale employed to collect survey responses was assessed using Cronbach's alpha coefficient. This metric gauges the consistency of a rating scale by examining the average correlation or internal coherence among the variables evaluated using the scale (Santos, 1999). Typically, a Cronbach's alpha coefficient value equal to or greater than 0.70 signifies that the scale is reliable (Nunnally, 1978). In this study, Cronbach's alpha coefficient value of 0.892 indicated that the collected data were reliable for analysis in the upcoming sections.

Due to the necessity of normal data distribution for many statistical tests, the Shapiro-Wilk test, a commonly used method for assessing data normality, was initially employed to evaluate the data (Darko & Chan, 2018). The standard alpha value of 0.05 was utilized for testing normality via the Shapiro-Wilk test. If the resulting p-value from the test is below the chosen alpha value, it suggests that the data do not adhere to a normal distribution. In this research, all p-values generated by the Shapiro-Wilk test were 0.000, indicating that the collected data deviated from a normal distribution. This outcome was anticipated since data gathered from relatively small samples typically do not exhibit a normal distribution (Shan et al., 2017). The non-normal distribution of data influenced the choice of statistical tests for data analysis.

4.2.2 Discussion of Results

The benefits of the residential building NZC retrofitting were ranked by employing the mean and standard deviation, a commonly utilized statistical technique for organizing respondent's perspectives in a descending manner. When multiple benefits and enablers shared identical mean scores, standard deviation was utilized. Subsequently, the benefit with the lowest standard deviation was assigned the highest rank (Darko & Chan, 2018). A smaller standard deviation indicates that the discrepancies in responses were not significantly large, thereby implying that the average is more likely to be representative of the majority (Staplehurst & Ragsdell, 2010). In addition, a one-sample t-test was conducted to evaluate the significant importance of benefits to the success of residential building NZC retrofitting. The resulting p-values below 0.05 indicated that all the benefits are significantly important. Table 4.1 indicates the results of all these statistical tests.

Table 4.1: Ranking of benefits from residential building NZC retrofitting.

Category	List of Benefits	Mean	Standard deviation	Significance (2-tailed)	Rank
Social benefits	Improve building comfort (thermal, natural, lighting, acoustic, etc.)	3.80	0.964	0.001	7
	Enhance the quality of life for occupants	3.46	0.994	0.048	13
	Increase efficiency and reliability of the building systems	3.50	0.953	0.026	12
	Provide better building appearance/ aesthetics	3.05	1.122	0.000	17
	Increase building usable time	3.08	1.309	0.001	16
	Increase indoor and outdoor environmental quality	3.43	0.950	0.021	15
	Create new job opportunities	3.43	0.888	0.039	14
Environmental benefits	Reduce environmental pollution	3.78	1.346	0.023	10
	Reduce energy consumption and secure energy supply	3.85	1.355	0.005	5
	Reduce carbon and GHG emissions	3.80	1.341	0.013	8
	Minimize adverse climatic effects	3.79	1.344	0.019	9
Economic benefits	Increase the building value	3.74	1.227	0.032	11
	Reduce energy costs	4.07	1.242	0.000	2
	Increase accessibility to incentives and subsidies	3.82	1.181	0.003	6
	Lower building maintenance costs	4.11	1.213	0.000	1
	Attractive return on investments	4.05	1.193	0.000	3
	Reduce vulnerability to fluctuating prices	3.86	1.257	0.002	4

As per Table 4.1, the mean scores denoting the significance of benefits range between 3.05 and 4.11. Given that all benefits received mean scores exceeding 3.00, the midpoint of the rating scale, this underscores the considerable importance of these aspects. This heightened significance can be linked to the overarching vision articulated in Hong Kong's Climate Action

Plan 2050, which emphasizes “zero-carbon emissions, livable city, sustainable development” (HKCAP, 2021). Hence, the identification of these benefits to advance the retrofitting of residential buildings to NZC emerges as a critical requirement within Hong Kong. Such identification stands to aid the Hong Kong government in formulating strategies aimed at combating climate change and attaining carbon neutrality. While recognizing the significance of all benefits, prioritizing them through ranking could offer policymakers, stakeholders, and advocates insights into where to concentrate efforts, thereby facilitating the prioritization of activities promoting NZC retrofitting in residential buildings.

Out of the 17 distinct benefits, three received mean scores surpassing 4.00. Specifically, “lower building maintenance costs” secured the top position with the highest mean score (4.11), indicating that it was perceived as the most crucial element. During the process of retrofitting residential buildings to NZC, improvements in the building envelope and energy systems present significant opportunities to boost the building performance. Consequently, retrofitting of existing buildings directly supports to reduce the expenses related to the repair and replacement while enhancing the building performances (Almeida & Ferreira, 2018). A comparative analysis of the maintenance costs between a conventional building and a retrofitted NZC building can effectively quantify the cost-effectiveness of retrofitting residential buildings to NZC. As a result, decision-makers can undertake life cycle cost assessments and advocate for the retrofitting of residential buildings to NZC, highlighting the potential long-term savings stemming from reduced maintenance costs.

“Reduce energy costs” obtained a mean score of 4.07, indicating the second position in the ranking. This finding is consistent with prior research, which demonstrates that energy consumption can decrease by 15% to 72% through retrofit strategies such as insulation, upgrading window glazing, installing shading devices, and implementing on-site energy generation (Aldossary et al., 2014, 2017; AlFaris et al., 2016). Accordingly, the adoption of energy-efficient practices helps in cutting down the upfront expenses associated with renewable energy by decreasing overall energy demand. Consequently, the retrofitting process for NZC significantly contributes to lowering energy costs. Given the availability of both renewable and non-renewable energy sources as NZC retrofit measures, it would be beneficial to establish a quantitative metric that outlines the minimum utilization of renewable energy sources based on the capacities of residential buildings. This approach would enhance energy performance by reducing energy demand from renewable sources, thus fostering more sustainable energy practices.

"Attractive return on investments" obtained a mean score of 4.05, indicating the third position in the ranking. This ranking is consistent with the top two positions, as both emphasize the aspect of profitability. Despite the substantial initial expenses associated with retrofitting residential buildings to NZC, there exists the potential for significant returns on investments. Notably, Charles et al. (2019) underscored that the return on investment for upgrades to the building envelope for low carbon emissions was estimated at 7.7 years. Moreover, the utilization of renewable energy in achieving NZC can attract government subsidies, with authorities potentially offering payments to building occupants for generating energy within residential buildings, thereby creating an additional avenue for profit through NZC retrofitting. To incentivize building occupants towards utilizing renewable energy for NZC, the Hong Kong government has introduced initiatives such as the "Feed-in Tariff" (FiT) (GovHK, 2024c). Establishing similar policies can play a pivotal role in encouraging occupants by highlighting the appealing return on investments achievable through NZC retrofitting, notwithstanding the high initial costs involved.

4.3 Research Framework

A research framework serves as a fundamental structure or conceptual model guiding collaborative research efforts, drawing on established theories or logical constructs (Simon & Goes, 2011), thereby being pivotal in generating fresh insights and knowledge. The present chapter has constructed a theoretical framework based on the works of Ohene et al. (2023) and Weerasinghe et al. (2024), as depicted in Figure 4.1. Specifically, Ohene et al. (2023)'s framework was utilized to comprehend the beneficial influence in attaining NZC buildings. Moreover, Weerasinghe et al. (2024)'s findings were employed to pinpoint various categories of benefits and primary methods for retrofitting existing buildings. This framework is instrumental in enhancing understanding of the benefits associated with transitioning existing building stock to NZC residential buildings. The positive symbol (+) associated with the proposed framework signifies that current benefits positively impact NZC retrofitting.

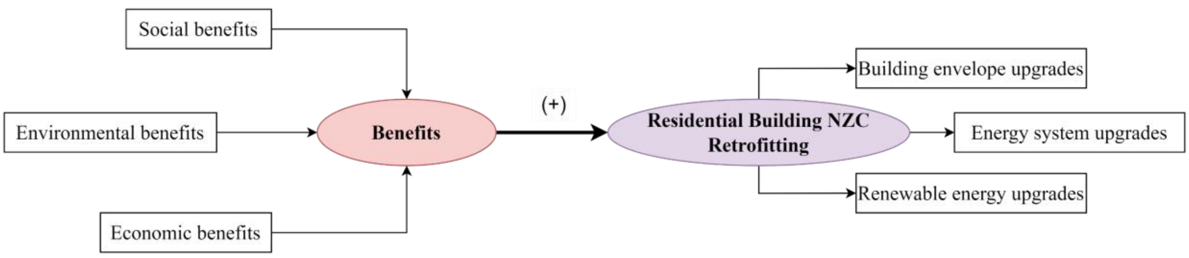


Figure 4.1: Research framework.

4.4 Hypotheses Development

According to Figure 4.1, economic, social, and environmental benefits have a direct impact on the promotion of residential building NZC retrofitting. Based on the literature findings, Table 4.2 summarizes the 4 constructs used to examine and model the relationship between benefits and the residential building NZC retrofitting. The review undertaken by Weerasinghe et al. (2024) explained that there are several measures classified as "building envelope upgrades" (BE), "energy system upgrades" (ES), and "renewable energy upgrades" (RE) that can be used in retrofitting to attain NZC residential buildings. In addition, based on the details in section

2.2.3, the categories of retrofitting measures were used as the measurement items to assess the residential building NZC retrofitting.

Table 4.2: Constructs and their respective measurement items.

Construct	Code	Measurement items
Economic benefits	EcB1	Increase the building value
	EcB2	Reduce energy costs
	EcB3	Lower building maintenance costs
	EcB4	Increase accessibility to incentives and subsidies
	EcB5	Attractive return on investments
	EcB6	Reduce vulnerability to fluctuating prices
Environmental benefits	EnB1	Reduce energy consumption and secure energy supply
	EnB2	Reduce carbon and GHG emissions
	EnB3	Minimize adverse climatic effects
	EnB4	Reduce environmental pollution
Social benefits	SoB1	Improve building comfort (thermal, natural, lighting, acoustic, etc.)
	SoB2	Provide better building appearance/ aesthetics
	SoB3	Increase efficiency and reliability of the building systems
	SoB4	Increase building usable time
	SoB5	Enhance the quality of life for occupants
	SoB6	Increase indoor and outdoor environmental quality
	SoB7	Create new job opportunities
Residential building NZC retrofitting	BE	Building envelope upgrades
	ES	Energy system upgrades
	RE	Renewable energy upgrades

Apart from the impacts of benefits on residential building NZC retrofitting, there is a mutual interaction between these three types of benefits. For instance, improvements in building comfort and energy system efficiency resulting from NZC retrofitting had a direct impact on lowering operational carbon emissions and energy costs, which are environmental and economic benefits, respectively. Thus, social benefits have a direct impact on economic and environmental benefits. Furthermore, increasing building value through NZC retrofitting has an impact on reducing energy consumption and carbon emissions, demonstrating the link between economic and environmental benefits. Based on this, the following hypotheses were proposed, indicating the relationship between benefits, and residential building NZC retrofitting. Figure 4.2 depicts the created model that incorporates the proposed hypotheses. Hypotheses are represented by the lines between the constructs in the model, and the direction of the arrow shows the hypothesized impact.

H1 – Social benefits have a positive influence on the residential building NZC retrofitting

H2 – Economic benefits have a positive influence on the residential building NZC retrofitting

H3 – Environmental benefits have a positive influence on the residential building NZC retrofitting

H4 – Social benefits have a positive influence on the economic benefits and enablers

H5 – Social benefits have a positive influence on the environmental benefits and enablers

H6 – Economic benefits have a positive influence on the environmental benefits and enablers

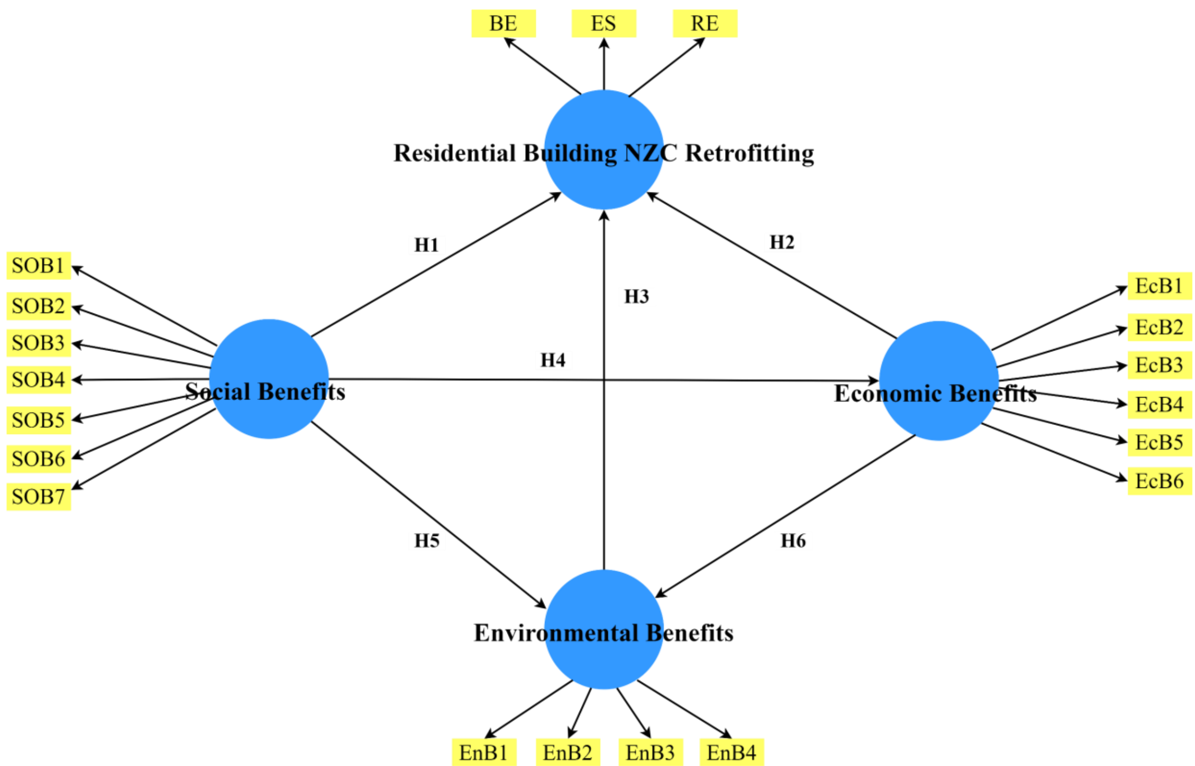


Figure 4.2: Hypothetical model indicating the relationship between benefits and residential building NZC retrofitting.

4.5 PLS-SEM Results

4.5.1 Evaluation of Measurement Model

Table 4.3 displays the evaluation outcomes for the measurement model's reliability and validity. During the PLS-SEM analysis, it was noted that factor loading values of the SoB2, SoB5, SoB7, EcB1, and EcB6 were lower than 0.5. Darko et al. (2018) asserted that measurement items with lower loadings should be eliminated as their impact on the model's explanatory power would be negligible, potentially skewing the estimates of other measurements. Following the removal of measurement items with factor loadings below 0.5, the model evaluation process had to be iterated until a reliable and valid model was attained (Darko et al., 2018). In light of that, the results of the finalized reliable model by removing the measurement items with factor loading below 0.5 are listed in Table 4.3.

Table 4.3: Results of measurement model evaluation.

Group	Code	Factor loading	AVE	Composite reliability	Cronbach's alpha
Economic benefits	EcB2	0.833	0.653	0.882	0.825
	EcB3	0.828	-	-	-
	EcB4	0.786	-	-	-
	EcB5	0.783	-	-	-
Environmental benefits	EnB1	0.853	0.677	0.893	0.841
	EnB2	0.846	-	-	-
	EnB3	0.838	-	-	-
	EnB4	0.750	-	-	-
Social benefits	SoB1	0.738	0.549	0.829	0.724
	SoB3	0.701	-	-	-
	SoB4	0.699	-	-	-
	SoB6	0.818	-	-	-
Residential building NZC retrofitting	BE	0.854	0.674	0.861	0.759
	ES	0.796	-	-	-
	RE	0.813	-	-	-

Table 4.3 demonstrated that all Cronbach's alpha values and composite reliability scores go beyond 0.7, representing a satisfactory level of internal consistency reliability for measurement items. Moreover, AVE and factor loadings exceeded 0.5, ensuring the convergent validity of the measurement model.

Tables 4.4-4.6 present the outcomes of evaluating the discriminant validity of measurement items. One approach to assess discriminant validity was through the Fornell and Lacker criterion. The bold values in Table 4.4 illustrated that that there are no correlations among constructs that surpass their AVE's square roots, showing the compliance with the Fornell and Lacker criterion. The evaluation of HTMT values was another method to ensure discriminant validity. Table 4.5 verified HTMT values above 0.9, confirming the discriminant validity of measurement items. In addition, bold values in Table 4.6 ensured the unavailability of cross-loading problems, confirming the discriminant validity of the measurement model by demonstrating the maximum loading on its relevant construct.

Table 4.4: Results of Fornell and Larcker criterion.

	Economic benefits	Environmental benefits	Social benefits	Residential building NZC retrofitting
Economic benefits	**0.808**			
Environmental benefits	0.460	**0.823**		
Social benefits	0.604	0.454	**0.741**	
Residential building NZC retrofitting	0.463	0.483	0.428	**0.821**

Table 4.5: HTMT values.

	Economic benefits	Environmental benefits	Social benefits	Residential building NZC retrofitting
Economic benefits				
Environmental benefits	0.534			
Social benefits	0.748	0.584		
Residential building NZC retrofitting	0.562	0.573	0.571	

Table 4.6: Cross-loadings of measurement items.

	Economic benefits	Environmental benefits	Social benefits	Residential building NZC retrofitting
EcB2	**0.833**	0.414	0.596	0.452
EcB3	**0.828**	0.343	0.514	0.374
EcB4	**0.786**	0.319	0.335	0.221
EcB5	**0.783**	0.930	0.447	0.395
EnB1	0.332	**0.853**	0.366	0.287
EnB2	0.399	**0.846**	0.404	0.487
EnB3	0.440	**0.838**	0.371	0.496
EnB4	0.315	**0.750**	0.348	0.256
SoB1	0.487	0.198	**0.738**	0.259
SoB3	0.371	0.430	**0.701**	0.267
SoB4	0.334	0.445	**0.699**	0.307
SoB6	0.578	0.279	**0.818**	0.413
BE	0.529	0.259	0.381	**0.854**

ES	0.265	0.610	0.289	**0.796**
RE	0.346	0.308	0.389	**0.813**

4.5.2 Evaluation of Structural Model

The results of the hypotheses are presented in Table 4.7. The finalized structural model indicating the relationship between benefits and residential building NZC retrofitting is illustrated in Figure 4.3 using the path coefficients and corresponding t-values.

Table 4.7: Hypotheses results.

Hypothesis Number	Hypothetical path	Path Coefficient	t-Value	p-Value	Interpretation
H1	Social benefits -> Residential building NZC retrofitting	0.139	1.660	0.097	Not supported
H2	Economic benefits -> Residential building NZC retrofitting	0.352	3.579	0.000	Supported
H3	Environmental benefits -> Residential building NZC retrofitting	0.261	2.511	0.012	Supported
H4	Social benefits - > Economic benefits	0.606	5.564	0.000	Supported
H5	Social benefits -> Environmental benefits	0.318	1.598	0.110	Not supported
H6	Economic benefits -> Environmental benefits	-0.052	0.461	0.645	Not supported

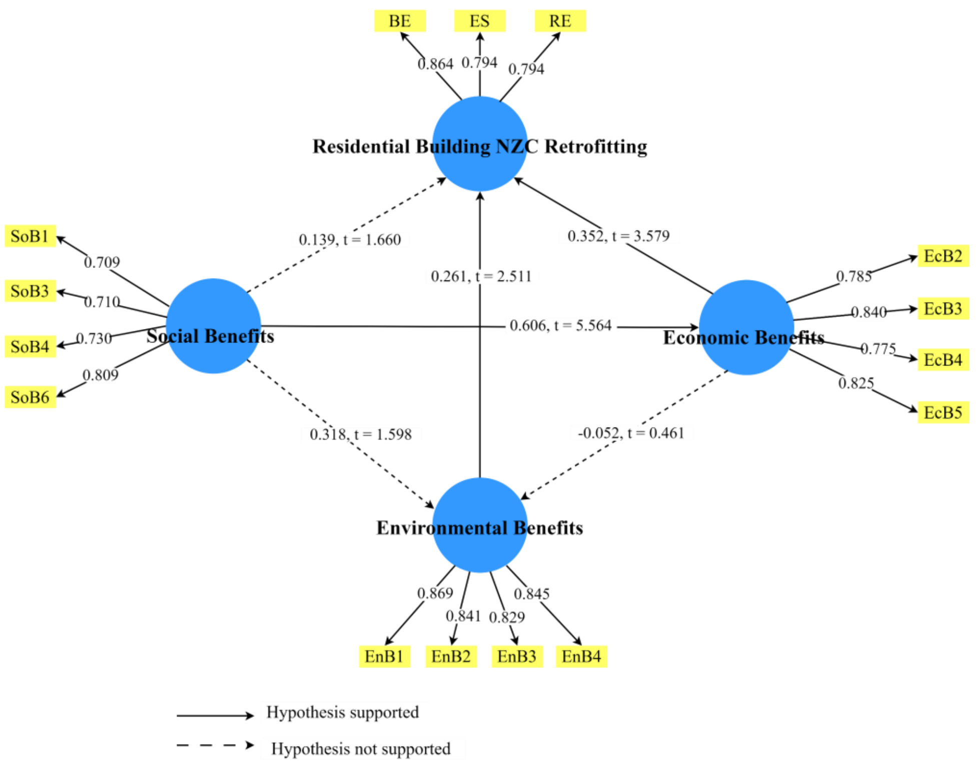


Figure 4.3: Structural model for the benefits of residential building NZC retrofitting.

As per the results of the structural model evaluation, only two paths connected to the residential building NZC retrofitting were significant. Accordingly, the paths connecting "economic benefits" and "environmental benefits" to the "residential building NZC retrofitting" were significant at 0.01 and 0.05 significance levels, indicating their t-values of 3.579 and 2.511, respectively. As a result, hypotheses H2 and H3 were supported with their t-values above 2.58 and 1.96, respectively. Murari (2015) noted that the influence of an independent variable can range from weak to moderate to high based on path coefficients in the ranges of 0.1-0.3, 0.3-0.5, and 0.5-1.0, respectively. Accordingly, "environmental benefits" have a weak influence on "residential building NZC retrofitting" while "economic benefits" have a moderate influence. Based on the path coefficient, "social benefits" highly influenced "economic benefits". In addition, hypothesis H4 was supported at a 0.01 significance level. Moreover, hypotheses concerning the influence of "social benefits" on "environmental benefits" (H5) and "economic benefits" on "environmental benefits" (H6) did not yield significance, owing to lower path coefficients and t-values.

4.5.3 Discussion of Results

4.5.3.1 Paths Towards Residential Building NZC Retrofitting

Among the three different benefits of residential building NZC retrofitting, only "economic benefits" and "environmental benefits" were significant at 0.01 and 0.05 significance levels, surpassing the threshold of 2.58 (t-value = 3.579) and 1.96 (t-value = 2.511) respectively. Jami et al. (2021) observed that building occupants tend to adopt behaviors aimed at achieving indoor comfort while minimizing the costs associated with energy retrofitting. Additionally, Maghsoudi Nia et al. (2022) highlighted that occupants prioritise personal satisfaction during the design or initial construction phase of a building, whereas their focus shifts towards financial benefits during the retrofitting stage. Further, building occupants may not believe that they would engage the "social benefits" as soon as after the NZC retrofitting similar to the energy cost savings gained from the NZC retrofitting. Hence, by retrofitting residential buildings with NZC, building occupants may prioritize their views toward economic and environmental benefits over attitudes toward social benefits. Therefore, it would be beneficial to develop policies and strategies focusing on "economic benefits" and "environmental benefits" to promote the NZC retrofitting of residential buildings in Hong Kong. However, in terms of significance, it is noteworthy that "economic benefits" exert a greater influence on residential building NZC retrofitting than "environmental benefits", as evidenced by the higher t-value of 3.579 compared to 2.511.

Significant factors within the category of "environmental benefits" in Hong Kong include '*reducing energy consumption and secure energy supply*', *'reducing carbon and GHG emissions', 'minimizing adverse climate effects',* and '*reducing environmental pollution*'. The primary objective of residential building NZC retrofitting is to mitigate operational carbon emissions by reducing operational energy consumption (Weerasinghe et al., 2024). Various retrofitting measures employed to attain NZC buildings exhibit differing levels of energy efficiency. For instance, Kaewunruen et al. (2019) demonstrated that enhancing the thermal efficiency of the building envelope, increasing wall thickness, and integrating smart windows could lead to energy savings of approximately 8.16%, 10.16%, and 14.65% respectively, as evidenced by a case study of Washington. In addition, D'Agostino et al. (2022) found that the addition of wall insulation could potentially result in energy consumption reductions of up to 17%. Further, the residential building NZC retrofitting plays a pivotal role in diminishing GHG emissions and alleviating resource depletion. Consequently, it is advisable to formulate policies that coordinate energy conservation efforts toward the achievement of NZC residential buildings. Currently in Hong Kong, the "energy efficiency and conservation policy" is available to reduce the energy consumption within residential buildings (GovHK, 2022). This policy attempts to reduce the electricity consumption from residential buildings by 20% to 30% from the 2015 level by 2050 and strives to attain 50% carbon neutrality by 2035.

4.5.3.2 Paths Towards Economic Benefits

The only path that comes toward the "economic benefits" is the "social benefits" and other paths are going outwards from the "economic benefits". The path connecting "economic benefits" and "social benefits" is significant at a 0.01 significance level by representing a t-value of 5.564, which is higher than the threshold of 2.58. The significance of the relationships between this path suggested that the emergence of "economic benefits" stems from the presence of "social benefits". For instance, social benefits such as "*enhance the quality of life for occupants*" and "*increase indoor and outdoor environmental quality*" play a critical role in shaping economic benefits such as "*lower building maintenance costs*" and "*reduce energy costs*" (Chang et al., 2022). Accordingly, even though "social benefits" are not significantly impacted to promote residential building NZC retrofitting, it significantly impact to promote "economic benefits", which are significantly impacted on residential building NZC. Therefore, it emphasizes the necessity of strategies to promote social benefits, given their substantial impact on residential building NZC retrofitting.

'*Lower building maintenance costs*' and '*increase the building value*' were identified as the most significant factors affecting "economic benefits" in Hong Kong. Bragolusi and D'Alpaos (2022) employed a life cycle cost approach to illustrate the substantial impact of residential building retrofitting on reducing operational and maintenance expenses. Their study, based on a residential building in Italy, underscored the cost-effectiveness of retrofitting initiatives. Wang and Xia (2015) emphasized that while the initial costs of retrofitting building energy systems to lower carbon emissions are considerable, the long-term benefits include significant cost savings through reduced operational and maintenance costs. This financial advantage is not restricted to developed regions but can also be realized in developing regions through NZC retrofitting of residential buildings. Fan and Xia (2017) further elucidated the long-term economic benefits of residential building retrofitting, pointing out that lower operations and maintenance costs, along with energy savings, result in significant long-term cost reductions. They suggested a multi-objective approach for optimizing retrofitting solutions, ensuring the best financial and energy returns for the investment. Accordingly, the economic benefits play a pivotal role in residential building NZC retrofitting, advocating for the promotion of retrofitting strategies to achieve NZC residential buildings. Hence, policymakers and decision-makers should emphasize the long-term financial gains stemming from residential building NZC retrofitting to incentivize building occupants to retrofit their existing buildings to NZC.

4.5.3.3 Paths Towards Environmental Benefits

Two hypotheses were developed to examine the relationship between environmental benefits and the perceived influence of social and economic benefits. These hypotheses posited that social and economic benefits would have a significant impact on the generation of environmental benefits. However, due to the inherently subjective nature of social benefits, which are often influenced by individual occupant behavior, occupants may have found it difficult to perceive or articulate a direct connection between social and environmental benefits. Similarly, economic benefits, such as "*lower building maintenance costs*", may not have been significantly associated by occupants with broader environmental impacts. Therefore, the hypotheses proposing a significant relationship between social and economic benefits with environmental benefits were not supported by the findings.

4.6 Chapter Summary, Contributions, and Limitations

The retrofitting of residential buildings to achieve NZC emerges as a timely solution in the pursuit of a zero-emissions built environment, crucial for addressing the challenges posed by climate change. Hence, this chapter centered on exploring the benefits associated with NZC retrofitting of residential buildings, with a specific focus on objectives; (1) to identify the significant benefits of residential building NZC retrofitting and (2) to model the relationship between benefits and residential building NZC retrofitting. Those were achieved through a combination of a literature review and a questionnaire survey. The literature review identified 17 benefits, and those were used to develop the questionnaire. The questionnaire survey was conducted focusing on building occupants in Hong Kong as the primary data collection method. Data analysis was conducted employing the mean score ranking method and PLS-SEM to achieve the objectives.

The mean score ranking method identified "*lower building maintenance costs*", "*reduce energy costs*", and "*attractive return on investments*" as the foremost benefits driving residential building NZC retrofitting. These factors emerged as key motivators for the adoption of NZC retrofitting practices. Subsequently, PLS-SEM was utilized to validate the developed hypothetical model, which was structured around the categorized benefits, and to examine the hypothesized relationships between residential building NZC retrofitting and these factors. The analysis highlighted the significant influence of "economic benefits" and "environmental benefits" on residential building NZC retrofitting, while "social benefits" were found to impact the generation of economic benefits. Notably, the remaining hypotheses concerning Hong Kong residential building NZC retrofitting did not exhibit a significant impact.

The chapter outcomes offer valuable insights for academia and industry professionals alike. Academics can leverage the identified benefits to enrich analyses aimed at improving residential building NZC retrofitting practices. In addition, the developed model for understanding the occupant perspectives on the benefits of residential building NZC retrofitting provides validated constructs for future studies. The identification and ranking benefits, along with economic benefits and environmental benefits, are primary drivers of adoption, offer actionable guidance for policymakers, retrofitting companies, and facility managers. These results suggest that promotional strategies should prioritize the communication of cost savings and environmental impacts, rather than emphasizing social benefits. Furthermore, government incentive schemes would be more effective if they were designed to target these key motivators. At the societal level, this study contributes directly to Hong Kong's carbon neutrality objectives by elucidating pathways to accelerate the adoption of residential building retrofitting. Accordingly, findings have the potential to inform public policy development and guide allocation of resources toward incentive programs that are primarily focused on economic considerations. As such, the outcomes of this study maintain substantial value for the NZC retrofitting research domain.

While the chapter successfully met its objectives, several limitations warrant consideration. Firstly, the data was confined to building occupants in Hong Kong; caution is advised in generalizing the findings. Future research should broaden its scope to a global scale and involve industry professionals to achieve comparable objectives. Secondly, the chapter utilized a non-probability sampling method, which, although limited, can still yield a representative sample. Thirdly, the identified benefits may evolve over time as residential building retrofitting to NZC progresses. Lastly, the chapter focused solely on residential buildings, suggesting the need for similar investigations across different building types to advance the zero-emissions built environment agenda.

CHAPTER FIVE[5]

5.0 Analysis and Modeling of the Relationship between the Challenges for Residential Building NZC Retrofitting

5.1 Introduction

Chapter 4 analyzes the benefits of residential building NZC retrofitting in Hong Kong, while the current chapter analyzes the challenges of residential building NZC retrofitting. Both chapters were developed based on the data collected through the questionnaire survey with building occupants in Hong Kong. As detailed in Table 3.6, 123 building occupants in Hong Kong have participated in the questionnaire survey. This chapter attempts to identify the critical challenges for residential building NZC retrofitting in Hong Kong and model their relationships. To achieve this, the literature findings in Table 2.2 were used for the questionnaire, and respondents were asked to rate the agreement level with these challenges using the five-point Likert scale; 1- strongly disagree, 2- disagree, 3- neutral, 4- agree, 5- strongly agree.

As explained in the previous chapter, the challenges were subjected to statistical analyses using the SPSS package. First, the reliability test and Shapiro-Wilk test were conducted to assess the reliability of the data and normal distribution. The 0.931 value of Cronbach's alpha coefficient confirmed that the data is reliable for analysis, and the data were non-normally distributed due to the p-values below 0.05 from the Shapiro-Wilk test. Further, one sample t-test was conducted to assess the significant impact of challenges for the residential building NZC retrofitting in

[5] This chapter has been partially published in Darko, A., Weerasinghe, L.N.K., Chan, A.P.C. (2025). A Partial Least Squares Structural Equation Modeling of Challenges to Existing Residential Building Net Zero Carbon Retrofitting. *Journal of Construction Engineering and Management*. *151*(8), 05025005.

Hong Kong. Next, similar to the previous chapter, mean score ranking and standard deviation were used to identify the critical challenges of residential building NZC retrofitting.

After the statistical tests, PLS-SEM was used for data analysis by establishing an interconnected network of effects among different challenges. The outcomes of this chapter are anticipated to offer important information for policymakers and practitioners, aiding in the reassessment of NZC retrofitting challenges and the formulation of effective policies and strategies to advance carbon neutrality within the built environment. They also contribute to the existing body of knowledge by unearthing the complex relationships between the challenges and their interactive effects revealing that the challenges influence one another and do not exist in isolation.

5.2 Identification of Critical Challenges for Residential Building NZC Retrofitting

The summary of the one-sample t-test results and mean score ranking analysis is illustrated in Table 5.1. The mean scores of the challenges range from 3.35 to 4.33. The interpretations for the ranking of the challenges are aligned with the descriptions in section 4.2.2. Further, p-values below 0.05 indicated that all the challenges significantly impact residential building NZC retrofitting.

Table 5.1: Ranking of challenges impact for residential building NZC retrofitting.

Category	List of challenges	Mean	Standard deviation	Significance (2-tailed)	Rank
Social challenges	Lack of knowledge and awareness on retrofitting (i.e., measures, benefits, and market)	4.12	0.764	0.000	3
	Unwillingness to invest in retrofitting	4.11	0.889	0.000	4
	Doubts regarding energy savings	4.11	1.007	0.000	5
	Resistance to change	3.93	1.077	0.000	8
Financial challenges	Complicate access to the finance data	3.85	0.807	0.000	10
	Lack of incentives and financial support	3.83	0.827	0.000	12
	High initial cost	3.79	0.852	0.000	14
	Uncertainty about payback time or return on investment	3.76	0.906	0.000	15
	Lack of reliability of the stakeholders who execute the work	3.96	0.793	0.000	6

Industrial and stakeholder challenges	Uncertainty about available technologies	3.82	0.769	0.000	13
	Lack of collaboration among stakeholders	3.50	0.953	0.000	24
	Lack of promotion	3.43	0.888	0.000	25
	Fragmentation of the supply chain	3.43	0.950	0.000	26
	Lack of professional knowledge and skills	3.38	0.935	0.042	27
	Poor understanding of sustainability and net zero targets	3.35	0.807	0.031	28
Administrative challenges	Lack of coordination mechanism	3.71	0.786	0.000	17
	Complex permit procedures	3.71	0.847	0.000	18
	Unavailability of standardized approaches to prevent climatic variations	3.70	0.809	0.000	19
	Lack of government support	3.67	0.825	0.000	20
	Lack of continuity, consistency, and flexibility of retrofit policies	3.67	0.882	0.000	21
	Lack of effective strategic programs	3.66	0.857	0.000	22
	Conflict with other building codes and regulations	3.52	0.899	0.000	23
Technical challenges	Complexity of existing buildings	3.93	0.847	0.000	7
	Lack of data and information	3.88	0.883	0.000	9
	Lack of widespread adoption of energy efficiency, renewable, and smart technologies	3.85	0.932	0.000	11
Geographical challenges	Obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)	4.33	0.775	0.000	1
	Difficulties due to high-rise, high-density urban environment	4.28	0.825	0.000	2
	Variation in climatic conditions	3.73	0.860	0.000	16

According to Table 5.1, "*obstacles to domestic renewable energy (i.e., technical limitations, and regulatory issues)*" and "*difficulties due to high-rise, high-density urban environments*" under "geographical challenges" have been ranked first and second with the highest mean scores of 4.33 and 4.28, respectively. It represented that building occupants have identified those two factors under "geographical challenges" as the critical challenges that hinder the NZC retrofitting of residential buildings in Hong Kong. Renewable energy sources play a pivotal role in achieving NZC residential buildings since they support reducing the operational carbon emissions as well as offset the operational carbon emissions and embodied carbon of retrofit materials (Weerasinghe et al., 2024). However, Hong Kong is a high-density urban region with a large amount of high-rise buildings (S. Liu et al., 2023). Therefore, the nature of multi-story buildings highly impacted the installation of PV panels and retrofitting of the building envelope and energy systems. Further, Li et al. (2017) also highlighted that Hong Kong has sufficient sunlight for solar water heating and solar panels to generate energy, but the small roof area due to the high-rise nature of buildings restricted energy generation. In addition, Li et al. (2017) mentioned that the inability to maintain a central water supply system due to the high-rise nature of residential buildings prevents the use of solar power for water heating. Accordingly, it would be beneficial to arrange a method from the Hong Kong government for residential building owners to invest in renewable energy sources to achieve NZC in their residential buildings by preventing the challenges created by the high-density urbanized nature and obstacles to domestic renewable energy.

According to the building occupants' responses, "*lack of knowledge and awareness on retrofitting*" under "social challenges" ranked the third critical challenge with a mean of 4.12. In achieving the NZC residential buildings from existing building stock in Hong Kong, it is vital to enhance the building occupant's knowledge of building retrofitting, energy savings, and cost benefits. Baumhof et al. (2018) also asserted that the knowledge and awareness of building occupants is a major factor that impacted the process of achieving NZC from the existing residential buildings. Further, building occupants are a key stakeholder in the process of retrofitting the residential buildings (Sleiman et al., 2024). Therefore, it would be interesting to develop necessary programs from the Hong Kong government to enhance the building occupant's awareness of the benefits of residential building NZC retrofitting.

5.3 Research Framework

A research framework is a foundational structure or conceptual model which directs collaborative research endeavors, drawing upon established theories and/ or logical constructs (Simon & Goes, 2011), thereby playing a crucial role in generating novel insights and knowledge. The current chapter developed a theoretical framework based on Ohene et al. (2023)'s and Weerasinghe et al. (2024)'s work, as shown in Figure 5.1. Specifically, the framework developed by Ohene et al. (2023) was used to understand the negative impact of challenges in achieving NZC buildings. Further, the findings of Weerasinghe et al. (2024) were used to identify the different categories of challenges and main ways of retrofitting existing buildings: (1) building envelope upgrades, (2) energy system upgrades, and (3) renewable energy upgrades. This framework would be valuable in acquiring an improved awareness of the challenges connected with delivering NZC residential buildings from the existing building stock because it illustrates the concerns that impede stakeholders from building NZC retrofitting. The suggested framework's negative sign (-) implies that current challenges have a negative impact on NZC retrofitting.

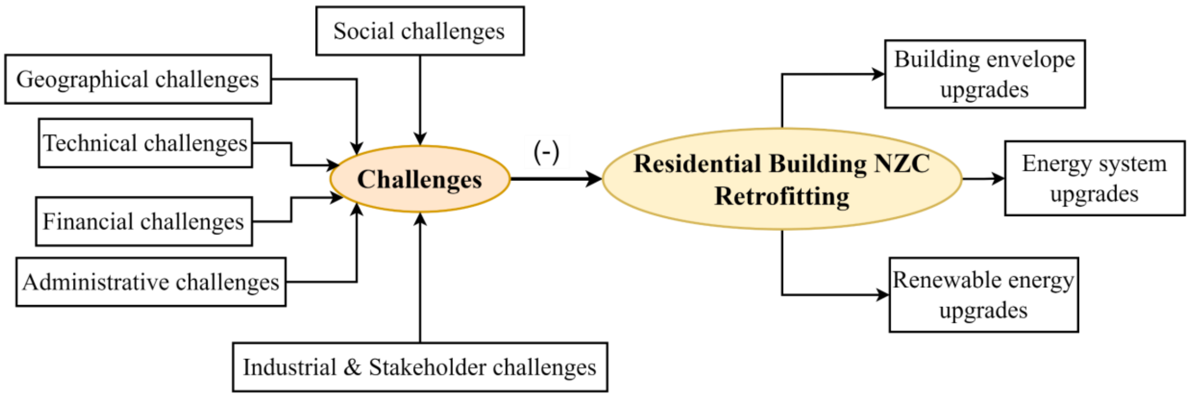


Figure 5.1: Research framework (Darko et al., 2025).

5.4 Hypotheses Development

Since building retrofitting is necessary for achieving a carbon-neutral built environment, prior studies have undertaken qualitative and quantitative assessments to evaluate the efficacy of various building retrofitting approaches in attaining NZC objectives (Luo, 2022; Weerasinghe et al., 2024). Among these methods, enhancements to the building envelope encompassing actions such as window upgrades, roof/wall insulation, enhancements to the energy systems such as hot water and HVAC, and the combination of energy from renewable sources such as solar panels, serve an essential role in the NZC retrofitting procedure. The optimization of the building envelope and energy systems serves to decrease operational carbon releases originating from the existing buildings, while the employment of energy from renewable sources aids in balancing and neutralizing any residual carbon emissions to attain NZC buildings (Weerasinghe et al., 2024). Therefore, these three categories of retrofitting methodologies are used in this chapter to measure NZC retrofitting in residential buildings (Table 5.2).

Despite the wide range of retrofitting solutions that include building envelope, energy systems, and renewable energy upgrades, challenges remain in the pursuit of NZC retrofitting for buildings. Prior research has thus delved into the identification of numerous challenges that impede the progress of NZC retrofitting endeavors in different regions. For instance, Baldwin et al. (2018), G. Liu et al. (2020), and Wang et al. (2024) identified notable challenges in China while Prabatha et al. (2020) and Tsenkova (2021) highlighted substantial challenges in Canada. Furthermore, Butt et al. (2021), Amoruso and Schuetze (2022b), Satre-Meloy et al. (2024), and Downing and Hsu (2024) have identified significant challenges in the United Kingdom, Korea, the United States, and New York, respectively. According to prior studies, inadequate collaboration among stakeholders, public hesitancy in adjusting attitudes towards retrofitting, and lack of data on the actual performance of retrofit strategies significantly impacted retrofitting residential buildings in China to NZC (Baldwin et al., 2018; G. Liu et al., 2020; Wang et al., 2024). The scarcity of data concerning embodied emissions and economic challenges were significant in Canada's efforts to retrofit existing buildings toward achieving zero emissions (Prabatha et al., 2020; Tsenkova, 2021). The economic challenges were more significant in Canada following the discontinuation of the "cap-and-trade" program after a government transition in 2018 (Tsenkova, 2021). Moreover, the shortage of qualified labor in the construction industry, high initial costs, funding shortfalls, and limited familiarity with emerging building technologies were critical challenges in the United Kingdom, Korea, the United States, and New York in their pursuit of zero emissions through residential building retrofitting (Amoruso & Schuetze, 2022b; Butt et al., 2021; Downing & Hsu, 2024; Satre-Meloy et al., 2024). The exploration of diverse challenges by previous studies is essential for effectively addressing these hurdles. Moreover, studies have grouped these challenges to facilitate more streamlined management approaches.

Accordingly, G. Liu et al. (2020) conducted a review and described the challenges focusing on technology, finance, administration, and knowledge/information. Marinelli et al. (2021) discussed technical, economic, and regulatory challenges through a thorough review. Recently, a comprehensive review was published by Weerasinghe et al. (2024) on building NZC retrofitting and grouped the challenges as financial, social, geographical, administrative, technical, and industrial and stakeholder challenges. Insights derived from the literature collectively indicate that these challenges can pose significant obstacles in residential building retrofitting to achieve NZC standards, thereby exerting a potentially adverse impact on residential building NZC retrofitting. Therefore, assessing the connection between these challenges and residential building NZC retrofitting represents a critical knowledge gap within the existing literature on NZC retrofitting.

Beyond the impact of challenges on building NZC retrofitting, there exists the potential for challenges to mutually influence one another. In this regard, G. Liu et al. (2020) noted the influence of administrative challenges such as lack of governmental support on social challenges, and the impact of technical challenges on administrative challenges. Furthermore, as elucidated by Pan and Pan (2019) and Attia et al. (2022), geographical challenges can impact administrative and industrial challenges, while financial challenges can exert an influence on social challenges. Moreover, although lacking empirical verification, it can be posited that technical and geographical challenges may also influence social challenges. Nevertheless, these assertions have been made in the absence of quantitative correlation analyses of the challenges. Therefore, there is a compelling necessity to construct a statistically validated network that depicts the interaction of challenges in the residential building NZC retrofitting.

Accordingly, PLS-SEM was used to assess the interaction of challenges in the residential building NZC retrofitting. The constructs and the measurement items used for PLS-SEM are shown in Table 5.2.

Table 5.2: Constructs and their associated measurement items.

Constructs	Code	Measurement items
Social challenges	SCH1	Resistance to change
	SCH2	Doubts regarding energy savings
	SCH3	Unwillingness to invest in retrofitting
	SCH4	Lack of knowledge and awareness on retrofitting (i.e., measures, benefits, and market)
Financial challenges	FCH1	Uncertainty about payback time or return on investment
	FCH2	High initial cost
	FCH3	Complicate access to the finance data
	FCH4	Lack of incentives and financial support
Industrial and Stakeholder challenges	ICH1	Lack of reliability of the stakeholders who execute the work
	ICH2	Uncertainty about available technologies
	ICH3	Lack of collaboration among stakeholders
	ICH4	Poor understanding of sustainability and net zero targets
	ICH5	Lack of professional knowledge and skills
	ICH6	Fragmentation of the supply chain
	ICH7	Lack of promotion
Administrative challenges	ACH1	Lack of government support
	ACH2	Complex permit procedures
	ACH3	Unavailability of standardized approaches to prevent climatic variations
	ACH4	Lack of coordination mechanism
	ACH5	Lack of continuity, consistency, and flexibility of retrofit policies
	ACH6	Lack of effective strategic programs
	ACH7	Conflict with other building codes and regulations
Technical challenges	TCH1	Complexity of existing buildings
	TCH2	Lack of data and information
	TCH3	Lack of widespread adoption of energy efficiency, renewable, and smart technologies
Geographical challenges	GCH1	Variation in climatic conditions
	GCH2	Difficulties due to high-rise, high-density urban environment

	GCH3	Obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)
Residential building NZC retrofitting	BE	Building envelope upgrades
	ES	Energy system upgrades
	RE	Renewable energy upgrades

To complete the gaps highlighted in the literature review, a hypothetical model was built, as indicated in Figure 5.2. The intention of this model is to provide a network of challenges that hinder residential building retrofitting by giving a better understanding of the way those challenges influenced one another and NZC retrofitting of residential buildings. By synthesizing insights from existing literature and employing literature-based assumptions, the following hypotheses in Table 5.3 are proposed. Hypotheses are represented by the lines between the constructs in the model, and the direction of the arrow shows the hypothesized impact (Figure 5.2).

Table 5.3: Proposed hypotheses.

Code	Hypothesis	References
H1	Administrative challenges have a negative influence on residential building NZC retrofitting	(Pan & Pan, 2019), (G. Liu et al., 2020), (Marinelli et al., 2021)
H2	Financial challenges have a negative influence on residential building NZC retrofitting	(Amoruso & Schuetze, 2022b), (G. Liu et al., 2020), (Marinelli et al., 2021)
H3	Geographical challenges have a negative influence on residential building NZC retrofitting	(Pan & Pan, 2019), (Ohene et al., 2022a)
H4	Industrial and stakeholder challenges have a negative influence on residential building NZC retrofitting	(Baldwin et al., 2018), (Pan & Pan, 2019), (G. Liu et al., 2020)
H5	Social challenges have a negative influence on residential building NZC retrofitting	(G. Liu et al., 2020), (Ohene et al., 2022a)
H6	Technical challenges have a negative influence on residential building NZC retrofitting	(G. Liu et al., 2020), (Marinelli et al., 2021), (Affandi et al., 2022)
H7	Administrative challenges significantly influence social challenges	(G. Liu et al., 2020)
H8	Financial challenges significantly influence social challenges	(Attia et al., 2022)
H9	Geographical challenges significantly influence social challenges	(Ohene et al., 2022a)
H10	Industrial and stakeholder challenges significantly influence social challenges	(Baldwin et al., 2018)
H11	Technical challenges significantly influence social challenges	(Affandi et al., 2022)

H12	Geographical challenges significantly influence administrative challenges	(Pan & Pan, 2019), (Chen et al., 2024)
H13	Technical challenges significantly influence administrative challenges	(Affandi et al., 2022)
H14	Financial challenges significantly influence administrative challenges	(Attia et al., 2022)
H15	Geographical challenges significantly influence financial challenges	(Pan & Pan, 2019), (Chen et al., 2024)
H16	Technical challenges significantly influence financial challenges	(Zheng et al., 2019)
H17	Geographical challenges significantly influence technical challenges	(Chen et al., 2024)
H18	Administrative challenges significantly influence industrial and stakeholder challenges	(Ohene et al., 2022a)
H19	Financial challenges significantly influence industrial and stakeholder challenges	(Attia et al., 2022)
H20	Geographical challenges significantly influence industrial and stakeholder challenges	(Pan & Pan, 2019)
H21	Technical challenges significantly influence industrial and stakeholder challenges	(D'Agostino et al., 2021)

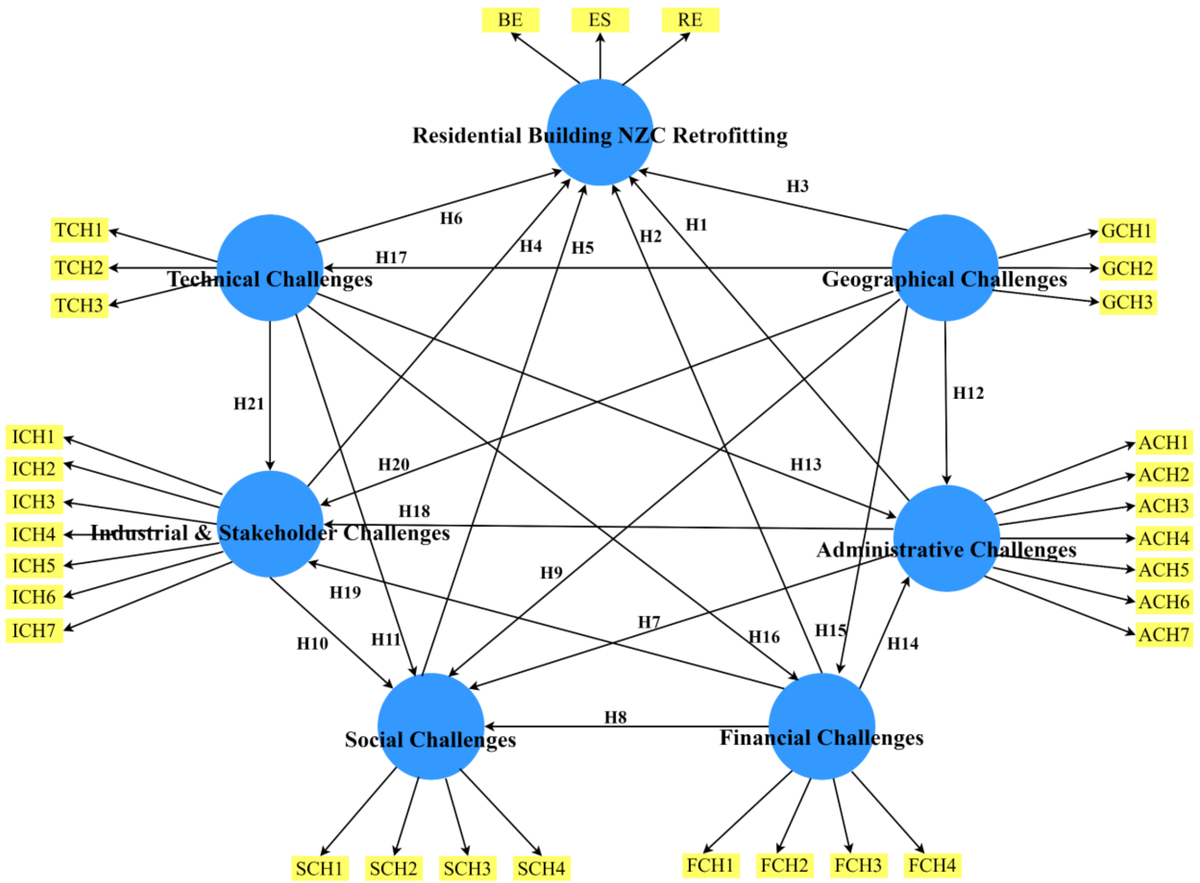


Figure 5.2: Hypothetical model of the challenges that hinder the NZC retrofitting of residential buildings.

5.5 PLS-SEM Results

5.5.1 Evaluation of the Measurement Model

Table 5.4 displays the evaluation outcomes for the measurement model's reliability and validity. The measurement items TCH1, GCH1, ICH1, ICH2, ICH4, FCH4, ACH1, ACH2, and ACH5 were eliminated due to their factor loading values falling below 0.5 in order to maintain the model's reliability and validity. Apart from the aforementioned observations, the interpretations regarding the results in Tables 5.5 – 5.7 align with the interpretations presented in section 4.5.1.

Table 5.4: Results of measurement model evaluation.

Construct	Measurement item	Factor loading	Cronbach's alpha	Composite reliability	AVE
Administrative challenges	ACH3	0.754	0.841	0.893	0.678
	ACH4	0.844	-	-	-
	ACH6	0.863	-	-	-
	ACH7	0.828	-	-	-
Financial challenges	FCH1	0.905	0.711	0.843	0.646
	FCH2	0.855	-	-	-
	FCH3	0.623	-	-	-
Geographical challenges	GCH2	0.886	0.738	0.884	0.793
	GCH3	0.894	-	-	-
Industrial and stakeholder challenges	ICH3	0.837	0.871	0.911	0.719
	ICH5	0.847	-	-	-
	ICH6	0.840	-	-	-
	ICH7	0.867	-	-	-
Social challenges	SCH1	0.796	0.825	0.883	0.654
	SCH2	0.832	-	-	-
	SCH3	0.783	-	-	-
	SCH4	0.823	-	-	-
Technical challenges	TCH2	0.925	0.856	0.932	0.873
	TCH3	0.944	-	-	-
Residential building NZC retrofitting	BE	0.846	0.759	0.861	0.673
	SE	0.809	-	-	-
	RE	0.806	-	-	-

Table 5.5: Results of Fornell and Larcker criterion.

	Administrative challenges	Financial challenges	Geographical challenges	Industrial and stakeholder challenges	Social challenges	Technical challenges	Residential building NZC retrofitting
Administrative challenges	**0.823**						

Financial challenges	0.427	**0.804**					
Geographical challenges	0.493	0.380	**0.890**				
Industrial and stakeholder challenges	0.687	0.174	0.468	**0.848**			
Social challenges	0.454	0.676	0.390	0.128	**0.809**		
Technical challenges	0.256	0.665	0.318	0.000	0.571	**0.934**	
Residential building NZC retrofitting	0.483	0.385	0.325	0.354	0.455	0.361	**0.821**

Table 5.6: HTMT values.

	Administrative challenges	Financial challenges	Geographical challenges	Industrial and stakeholder challenges	Social challenges	Technical challenges	Residential building NZC retrofitting
Administrative challenges							
Financial challenges	0.569						
Geographical challenges	0.623	0.534					
Industrial and stakeholder challenges	0.788	0.364	0.572				
Social challenges	0.534	0.869	0.480	0.213			
Technical challenges	0.299	0.840	0.395	0.127	0.664		
Residential building NZC retrofitting	0.573	0.533	0.429	0.409	0.562	0.452	

Table 5.7: Cross-loadings of measurement items.

	Administrative challenges	Financial challenges	Geographical challenges	Industrial and stakeholder challenges	Social challenges	Technical challenges	Residential building NZC retrofitting
ACH3	**0.754**	0.347	0.347	0.454	0.314	0.222	0.261
ACH4	**0.844**	0.350	0.436	0.624	0.399	0.233	0.500
ACH6	**0.863**	0.329	0.450	0.624	0.330	0.164	0.294
ACH7	**0.828**	0.381	0.384	0.544	0.437	0.224	0.497
FCH1	0.335	**0.905**	0.325	0.039	0.654	0.645	0.306
FCH2	0.238	**0.855**	0.228	-0.040	0.566	0.653	0.310
FCH3	0.477	**0.623**	0.370	0.477	0.381	0.263	0.316
GCH2	0.434	0.339	**0.886**	0.386	0.366	0.285	0.269
GCH3	0.444	0.337	**0.894**	0.446	0.330	0.281	0.309
ICH3	0.586	0.236	0.499	**0.837**	0.165	0.025	0.345
ICH5	0.499	0.019	0.371	**0.847**	-0.006	-0.183	0.218
ICH6	0.557	0.087	0.298	**0.840**	0.054	0.042	0.301
ICH7	0.664	0.202	0.392	**0.867**	0.179	0.075	0.314
SCH1	0.317	0.489	0.165	0.027	**0.796**	0.365	0.220
SCH2	0.338	0.582	0.276	-0.008	**0.832**	0.540	0.370
SCH3	0.388	0.548	0.319	0.194	**0.783**	0.405	0.395
SCH4	0.410	0556	0.452	0.175	**0.823**	0.508	0.445
TCH2	0.199	0.633	0.246	-0.007	0.485	**0.925**	0.256
TCH3	0.275	0.611	0.342	0.006	0.575	**0.944**	0.408
BE	0.252	0.378	0.244	0.162	0.522	0.362	**0.846**
SE	0.605	0.266	0.309	0.505	0.264	0.167	**0.809**

RE	0.299	0.308	0.238	0.168	0.343	0.382	**0.806**

5.5.2 Evaluation of Structural Model

Figure 5.3 depicts the structural model showcasing the impacts of challenges on residential building NZC retrofitting and how various challenges influence each other. In Figure 5.3, path coefficients and respective t-values were used to indicate the significance and the influence of challenges for residential building NZC retrofitting.

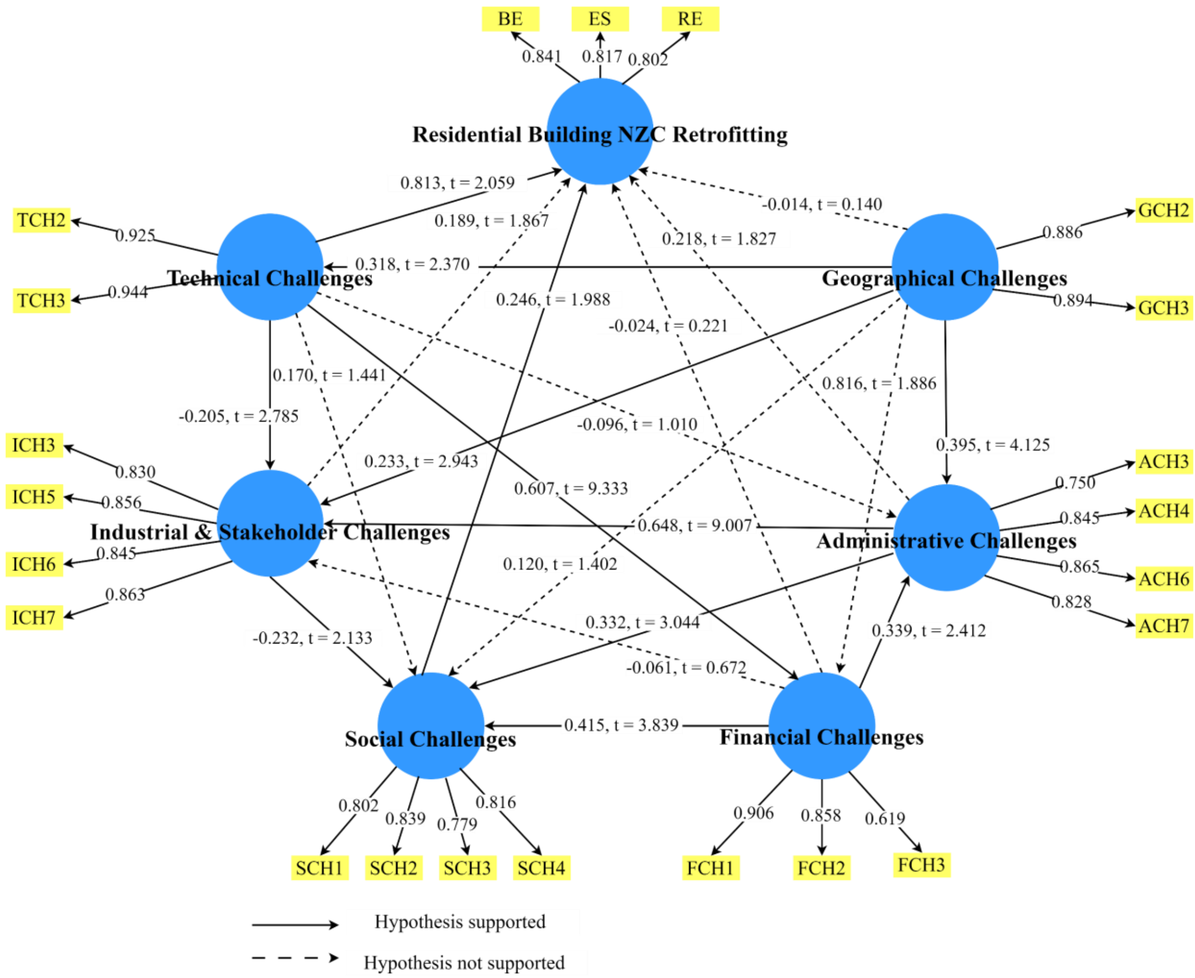


Figure 5.3: Structural model of challenges to residential building NZC retrofitting.

Accordingly, out of the 21 paths connecting challenges, residential building NZC retrofitting, and different challenge categories, only 12 paths were found to be significant, with t-values surpassing 1.96 and 2.58. The paths connecting "social challenges" and "technical challenges" to "residential building NZC retrofitting" had t-values greater than 1.96 (1.988 and 2.059

respectively) indicating that hypotheses H5 and H6 supported at 0.05 significant level. Further, the path coefficients represented that "technical challenges" are highly influenced on "residential building NZC retrofitting" while "social challenges" had a weak influence. In addition, paths connecting "industrial and stakeholder challenges" to "social challenges", "financial challenges" to "administrative challenges", and "geographical challenges" to "technical challenges" were supported at a 0.05 significant level since they represented 2.133, 2.412, and 2.370 t-values which are greater than 1.96 (Table 5.8). Further, hypotheses H7, H8, H12, H16, H18, H20, and H21 were supported at a significant level of 0.01 since the paths connecting "administrative challenges" to "social challenges", "financial challenges" to "social challenges", "geographical challenges" to "administrative challenges", "technical challenges" to "financial challenges", "administrative challenges" to "industrial and stakeholder challenges", "geographical challenges" to "industrial and stakeholder challenges", and "technical challenges" to "industrial and stakeholder challenges" had t-values of 3.044, 3.839, 4.125, 9.333, 9.007, 2.943, and 2.785 respectively which are greater than 2.58 (Table 5.8). However, paths connecting the hypotheses H1, H2, H3, H4, H9, H11, H13, H15, and H19 had t-values lower than 1.65, 1.96, or 2.58, and therefore, those hypotheses were not supported.

Table 5.8: Hypotheses results.

Hypothesis Number	Hypothetical Path	Path Coefficient	t-Value	p-Value	Interpretation
H1	Administrative challenges -> Residential building NZC retrofitting	0.218	1.827	0.068	Not supported
H2	Financial challenges -> Residential building NZC retrofitting	-0.024	0.221	0.825	Not supported
H3	Geographical challenges -> Residential building NZC retrofitting	-0.014	0.140	0.889	Not supported
H4	Industrial and stakeholder challenges -> Residential building NZC retrofitting	0.189	1.867	0.062	Not supported
H5	Social challenges -> Residential building NZC retrofitting	0.246	1.988	0.047	Supported
H6	Technical challenges -> Residential building NZC retrofitting	0.183	2.059	0.040	Supported
H7	Administrative challenges -> Social challenges	0.332	3.044	0.002	Supported
H8	Financial challenges -> Social challenges	0.415	3.839	0.000	Supported

H9	Geographical challenges -> Social challenges	0.120	1.402	0.161	Not supported
H10	Industrial and stakeholder challenges -> Social challenges	-0.232	2.133	0.033	Supported
H11	Technical challenges -> Social challenges	0.170	1.441	0.150	Not supported
H12	Geographical challenges -> Administrative challenges	0.395	4.125	0.000	Supported
H13	Technical challenges -> Administrative challenges	-0.096	1.010	0.313	Not supported
H14	Financial challenges -> Administrative challenges	0.339	2.412	0.016	Supported
H15	Geographical challenges -> Financial challenges	0.186	1.886	0.059	Not supported
H16	Technical challenges -> Financial challenges	0.607	9.333	0.000	Supported
H17	Geographical challenges -> Technical challenges	0.318	2.370	0.018	Supported
H18	Administrative challenges -> Industrial and stakeholder challenges	0.648	9.007	0.000	Supported
H19	Financial challenges -> Industrial and stakeholder challenges	-0.061	0.672	0.501	Not supported
H20	Geographical challenges -> Industrial and stakeholder challenges	0.233	2.943	0.003	Supported
H21	Technical challenges -> Industrial and stakeholder challenges	-0.205	2.785	0.000	Supported

5.5.3 Discussion of Results

5.5.3.1 Paths Toward Residential Building NZC Retrofitting

Among the six different challenges, only "technical challenges" and "social challenges" show significant effects on the residential building NZC retrofitting in Hong Kong. The paths linking "technical challenges" and "social challenges" to "residential building NZC retrofitting" exhibit a significance at 0.05, as indicated by t-values of 2.059 and 1.988, respectively, surpassing the threshold of 1.96. The other hypotheses developed based on "administrative challenges", "industrial and stakeholder challenges", "financial challenges", and "geographical challenges" were not supported due to their lower t-values.

Given that the challenges such as '*lack of coordination mechanism*' and '*unavailability of standardized approaches to prevent climatic variations*' considered under "administrative challenges" are handled by organizational level professionals, building occupants may not understand the significant impact of them for the residential building NZC retrofitting. Similarly, the “industrial and stakeholder challenges” may not be visible to the building occupants even if they exist within the industry. In terms of “financial challenges”, building occupants may not interpret these as significant, particularly considering the financial benefits that can be gained through the NZC retrofitting. Additionally, with the long-term existence of occupants in Hong Kong, they may not consider that there is a significant impact from “geographical challenges” to the residential building NZC retrofitting. As a result, the hypotheses related to the “administrative challenges”, “industrial and stakeholder challenges”, “financial challenges”, and “geographical challenges” were not supported, while hypotheses related to “social challenges” and “technical challenges” were supported.

Therefore, it is imperative to develop strategies that specifically address the “technical challenges” and “social challenges” in order to foster the widespread adoption of NZC retrofitting of existing residential buildings in Hong Kong, thereby contributing to creating a built environment more sustainable and achieving the targets outlined in the Paris Agreement. However, in terms of significance, it is noteworthy that “technical challenges” exert a greater influence on residential building NZC retrofitting than “social challenges”, as evidenced by the higher t-value of 2.059 compared to 1.988.

Among factors under “technical challenges”, ‘*lack of widespread adoption of energy efficiency, renewable, and smart technologies*’ were recognized as significant factors affecting “technical challenges” in Hong Kong. This challenge was highlighted in a review conducted by Li et al. (2017), who especially investigated the potential for low-carbon retrofitting of residential buildings in Hong Kong. The authors elaborated that limited roof areas of high-rise residential buildings hampered the incorporation of renewable energy sources. A notable example is the retrofitting of a McDonald’s restaurant in the Tai Wo area, Hong Kong, as the first attempt at achieving zero carbon emissions during August 2023 (Link, 2023). Therefore, the government should actively promote energy-saving and renewable energy technologies by developing a robust market for these technologies, thereby mitigating the "technical challenges". Moreover, another significant factor impacting the "technical challenges" is '*lack of data and information*'. This has been identified as a shared challenge that underscores the common issue of inadequate database maintenance in both developed and developing regions concerning carbon emissions and energy consumption data. The unavailability of a standardized data set in Hong Kong for capturing embodied carbon data has highly impacted building retrofitting and researchers have used data sourced from a Chinese standardized database by tailoring it to the local context of Hong Kong to achieve zero emissions from existing buildings (S. Liu et al., 2023). However, to address the challenge of '*lack of data and information*', China has implemented heating metering devices in retrofitted buildings to gather post-retrofit data (G. Liu et al., 2020). Moreover, Canada (Prabatha et al., 2020), Malaysia (Affandi et al., 2022), and Sri Lanka (Madushika & Lu, 2024) also experienced the inadequacy of data related to energy and carbon when retrofitting buildings to zero emissions. Consequently, storing such collected data in a dedicated database can facilitate its future use in similar building retrofitting processes (Liang et al., 2019). The data collected reveals that existing buildings in Hong Kong are predominantly old, which may explain the scarcity of data information required for NZC retrofitting. Therefore, it would be advantageous to establish a comprehensive database of existing buildings and seek consultations and support from industry experts to gather the necessary information in order to mitigate the existing "technical challenges" and promote residential building NZC retrofitting in Hong Kong.

5.5.3.2 Paths Toward Social Challenges

Among different paths connecting to "social challenges" from "administrative challenges", "financial challenges" and "industrial and stakeholder challenges" demonstrate significant levels of 0.01 and 0.05, as specified by t-values of 3.044, 3.839, and 2.133, respectively. The paths connecting from “technical challenges” and “geographical challenges” to “social challenges” did not have a significant impact. The social challenges are primarily arising from the occupant’s attitudes and the culture (Jami et al., 2021). With the long-term residence in Hong Kong, building occupants may believe urbanized nature is normal in Hong Kong, and there may not be a significant impact from “geographical challenges” to the “social challenges”. In addition, identified “technical challenges” may not significantly impact the generation of negative attitudes toward building NZC retrofitting. Therefore, the hypotheses developed based on the paths connecting from “technical challenges” and “geographical challenges” to “social challenges” were not supported, while the other paths were supported.

The significance of the relationships between these paths suggested that the emergence of “social challenges” stems from the presence of “administrative challenges”, “financial challenges”, and “industrial and stakeholder challenges”. For instance, the ‘*lack of effective strategic programs*’ aimed at promoting NZC retrofitting of residential buildings and ‘*uncertainty about payback time or return on investment*’ could lead to occupants being reluctant to undertake retrofitting efforts. Further, G. Liu et al. (2020) highlighted that the ‘*lack of coordination mechanisms*’ within the institutions has generated doubts among building occupants regarding energy saving. Additionally, industrial challenges such as ‘*lack of collaboration among stakeholders*’ and ‘*lack of promotions’* might contribute to occupants’ reluctance to invest in retrofitting projects. Therefore, addressing the prevalent “administrative challenges”, “financial challenges”, and “industrial and stakeholder challenges” is crucial, as they play a significant role in generating “social challenges” that adversely impact residential building NZC retrofitting.

‘*Doubts regarding energy savings*’, ‘*resistance to change*’, ‘*lack of knowledge and awareness on retrofitting*’, and ‘*unwillingness to invest in retrofitting*’ are the underlying factors that affect the “social challenges”. These factors mutually contribute to impeding the adoption of NZC retrofitting. Moreover, it is essential to realize the interdependencies among these underlying factors. For instance, the presence of uncertainties among building occupants regarding the NZC retrofitting process can lead to a reluctance to invest in such initiatives. Further, this resistance may be rooted in a limited understanding of the performance and benefits associated with NZC retrofitting.

Promoting awareness among building occupants regarding the concept of NZC retrofitting is important for successfully converting the existing buildings to NZC. This is endorsed by Baumhof et al. (2018) who highlighted the significance of equipping building occupants with knowledge about retrofitting measures to enhance their confidence and receptiveness towards such initiatives. Therefore, it would be highly advantageous to furnish building occupants with information pertaining to the benefits of NZC retrofitting, along with financial support. This may have the potential to enhance the willingness of occupants to invest in NZC retrofitting. However, the relatively low rate of NZC retrofitting observed in Hong Kong indicates a prevailing reluctance among occupants to engage in NZC retrofitting due to the lack of awareness. In light of this situation, it becomes imperative to develop knowledge and information policies specific to NZC retrofitting in order to address “social challenges”.

‘*Unwillingness to invest in retrofitting*’ is a major challenge for residential building retrofitting in Hong Kong due to split incentives. Split incentives commonly manifest between tenants and building owners during the retrofitting of residential buildings, as tenants derive benefits from the costs incurred by the owner (Melvin, 2018). Research by Gibb and Chu (2024) indicates that, on average, 49% of the population in Hong Kong resides in rented accommodations. Their findings highlighted that building owners exhibit reluctance to retrofit existing buildings with energy-efficient measures due to tenant's unwillingness to bear higher rental expenses. To address this issue, providing low-interest loans to building owners in Hong Kong, similar to procedures in the Netherlands (Vega et al., 2022), may assist in tackling the split incentives challenge. Furthermore, more studies are needed to evaluate policies aimed at minimizing this difficulty and encouraging building owners to undertake residential building retrofitting targeting NZC.

5.5.3.3 Paths Toward Administrative Challenges

Both paths connecting "geographical challenges" and "financial challenges" to "administrative challenges" demonstrate a significant level of 0.01 and 0.05, as indicated by t-values of 4.125 and 2.412, respectively. However, the path connecting from "technical challenges" to "administrative challenges" did not demonstrate a significance level. Given that both "technical challenges" and "administrative challenges" are handled by the professional at organization levels, occupants may be unable to understand the direct impact. As a result, the hypotheses developed based on paths connecting "technical challenges" to "administrative challenges" were not supported, while paths connecting "geographical challenges" and "financial challenges" to "administrative challenges" were supported.

The examination of these paths suggested that certain underlying "administrative challenges" could originate from the underlying "geographical challenges" and "financial challenges". For instance, '*difficulties due to high-rise, high-density urban environment'* may impede the development of '*strategic programs*' aimed at controlling carbon emissions from existing residential buildings. Chen et al. (2024) have contended that high-rise, densely populated cities contribute significantly to carbon releases, complicating administrative efforts toward achieving zero emissions. Additionally, the '*high initial costs*' and '*uncertainty on the payback* *time*' influenced the development of 'strategic programs' toward NZC residential buildings (Attia et al., 2022). Accordingly, it is evident that "geographical challenges" and "financial challenges" exert a substantial influence on "administrative challenges". Hence, effective strategies are essential to address and alleviate "geographical challenges" and "financial challenges" to mitigate "administrative challenges".

Furthermore, a total of four factors have been identified to influence the "administrative challenges" as '*lack of effective strategic programs*', '*conflicts with other building codes and regulations*', '*lack of coordination mechanism*', and '*unavailability of standardized approaches to prevent climatic variation*'. It is noteworthy that the underlying factors contributing to the "administrative challenges" exhibit interdependencies. For instance, the '*lack of effective strategic programs*' may result in misunderstandings regarding other building regulations due to the '*lack of coordination mechanisms*', leading to '*conflicts with other building codes and regulations*'.

Accordingly, it is advisable to establish a certificate system or grading system specifically tailored for NZC retrofitted residential buildings to tackle the challenges stemming from the '*lack of effective strategic programs*' and '*conflicts with other building codes and regulations*'. Therefore, similar to the existing green rating tools, the development of an assessment system dedicated to NZC-retrofitted residential buildings would prove beneficial. These assessment systems can subsequently serve as a supportive mechanism for the formulation of flexible policies pertaining to residential building NZC retrofitting. The presence of a '*lack of coordination mechanisms*' is another major challenge in the context of Hong Kong. G. Liu et al. (2020) discussed an identical problem encountered in China, citing conflicting stakeholder interests and the inherent difficulties in aligning these interests due to the lack of development of institution-related platforms. However, this difficulty is likely compounded in Hong Kong by data collection and administration challenges, as data is scattered among several departments, such as the Building Department and the Electrical and Mechanical Services Department. Consequently, the coordination of disparate departments poses a formidable challenge for stakeholders in achieving effective collaboration.

In Hong Kong, it is important to acknowledge the inherent complexity of energy usage patterns resulting from a high number of flats within a single building occupied by diverse residents. This complication poses challenges in achieving an effective and significant decrease in carbon. Consequently, for high-rise buildings situated in densely populated urban areas, it is recommended to devise separate NZC policy targets for residential and non-residential buildings to enhance the flexibility, consistency, and continuity of retrofit policies. Furthermore, the revision of building energy codes based on carbon reduction requirements, accompanied by the incorporation of additional credits for carbon reduction within the BEAM Plus rating system, would contribute to mitigating the aforementioned "administrative challenges" encountered in Hong Kong.

5.5.3.4 Paths Toward Industrial and Stakeholder Challenges

The paths connecting "administrative challenges", "geographical challenges" and "technical challenges" to "industrial and stakeholder challenges" demonstrate a significant level of 0.01, as implied by t-values of 9.007, 2.943, and 2.785. The analysis of these paths suggested that underlying "industrial and stakeholder challenges" may have originated from the existing "administrative challenges", "geographical challenges", and "technical challenges". For instance, the obstacles arising from high-rise, high-density urban environments may affect the promotion of retrofitting strategies to achieve NZC. Additionally, the '*lack of coordination mechanisms*' to achieve NZC residential buildings could lead to the '*lack of collaboration among stakeholders*', a crucial element in realizing NZC buildings (Ohene et al., 2022a).

D'Agostino et al. (2021) interpreted that the inadequate adoption of energy-efficient and renewable technologies can impede the development of integrated markets for these technologies. Further, it is clear that there is no impact from the "financial challenges" for the generation of "industrial and stakeholder challenges" such as '*lack of collaboration among stakeholders'* and *'lack of professional knowledge and skills'*. Given that the hypothesis representing "financial challenges" and "industrial and stakeholder challenges" was not supported. On the contrary, professionals specializing in NZC retrofitting can contribute to addressing the "administrative challenges", "geographical challenges" and "technical challenges" to mitigate their influence on the "industrial and stakeholder challenges".

The loading values of factors; '*lack of collaboration among stakeholders*', '*lack of promotion*', '*Lack of professional knowledge and skills'*, and '*fragmentation of the supply chain*' indicate their influence on the "industrial and stakeholder challenges". Notably, the supply chain for renewable technologies can be segmented due to the presence of suppliers from different geographical locations, leading to the '*fragmentation of supply chain*' and subsequently impacting the '*lack of promotions*'. Furthermore, the absence of an adequate number of professionals in the domain can contribute to less collaboration among stakeholders. Accordingly, it is evident that there exists an interconnectedness among the factors influencing "industrial and stakeholder challenges". Therefore, effective strategies needed to be proposed to mitigate those factors to address the "industrial and stakeholder challenges".

Professionals are pivotal in assessing the performance of existing residential buildings and ensuring compliance with NZC standards, offering crucial services to building occupants. In the United Arab Emirates, training programs have been introduced to enhance the expertise of professionals engaged in building retrofitting, aiming at fostering a sustainable built environment (G. Liu et al., 2020). In addition, developed regions like Germany and France stress the need for architects involved in retrofitting projects to possess adequate knowledge and experience for sustainable design creation (G. Liu et al., 2020). Therefore, educational initiatives targeting professionals and workers can develop their knowledge of NZC retrofitting, ensuring a pool of qualified experts. The HKGBC has taken steps to organize events and training programs focusing on NZC for professionals to address the "industrial and stakeholder challenges".

Baldwin et al. (2018) highlighted the importance of involving multiple stakeholders in promoting residential building retrofitting endeavors. Similarly, in the domain of residential building NZC retrofitting, numerous stakeholders, including government entities, are involved. Establishing enhanced coordination mechanisms among these stakeholders by refining work processes and delineating responsibilities is crucial. The early efforts in NZC retrofitting in Hong Kong indicate that effective stakeholder coordination facilitates the exchange of market insights and experiences in NZC retrofitting projects (Link, 2023). Therefore, creating partnership platforms to boost communication and collaboration among institutions and stakeholders can significantly enhance the successful retrofitting of existing residential buildings towards NZC.

5.5.3.5 Path Toward Financial Challenges

The path connecting "technical challenges" to "financial challenges" demonstrates a significant level of 0.01, as designated by a t-value of 9.333. In addition, the path connecting "geographical challenges" to "financial challenges" did not show significance. The less impact from the "geographical challenges" for the "financial challenges", such as '*complicate access to the finance data*' and '*uncertainty about payback time or return on investment',* highlights the reasons behind the unsupported hypothesis. The significance between "technical challenges" and "financial challenges" shows that existing "financial challenges" may be created by existing "technical challenges". For instance, the estimation of the economic returns derived from retrofitted residential buildings depends upon the available '*data and information*' of the existing buildings. Further, Zheng et al. (2019) also asserted that historical data related to energy consumption and carbon emission are the main sources to calculate the '*return on investments*' in the NZC retrofitting efforts. Additionally, the '*high initial costs*' of the retrofitting strategies may be due to the '*lack of widespread adoption of energy efficiency and renewable technologies*'. Hence, it is evident the significant connection between "technical challenges" and "financial challenges".

The factor with the highest loading value for "financial challenges" is identified as the '*uncertainty about payback time or return on investment*'. Implementing innovative strategies to alleviate financial constraints for building occupants and investors is crucial in addressing this challenge (Ohene et al., 2022a). Making financial information publicly available and offering detailed cost breakdowns to building occupants and investors can help in tackling the '*complicated access to finance data*'. The NZC retrofitting of existing residential buildings often faces obstacles such as large starting costs and extended payback periods (Hrovatin & Zorić, 2018), emphasizing the importance of capital availability in this context (G. Liu et al., 2020). The significant "financial challenge" of '*uncertainty about payback time or return on investment*' in Hong Kong may stem from limited capital availability for retrofitting efforts, especially given the complexities of buildings and their related high initial costs. Baek and Park (2012) highlighted that investment banks in Germany offered low-interest loans specifically for building retrofitting. Therefore, multiple financial support mechanisms from the government and other financial organizations, including incentives, low-interest loans, tax reductions, special funds, and rewards can significantly advance the retrofitting of residential buildings towards NZC. Furthermore, Germany has developed policies that provide financial support targeted at low-income residents. This serves as a valuable reference for developed regions such as Hong Kong, as addressing the concerns of low-income residents, who may be discouraged by high investment costs, can be crucial in promoting NZC retrofitting strategies.

5.5.3.6 Path Toward Technical Challenges

The path connecting “geographical challenges” to “technical challenges” demonstrates a significant level of 0.05, as designated by a t-value of 2.370. The correlation between “geographical challenges” and “technical challenges” reveals that the underlying “technical challenges” arise as a consequence of the prevailing “geographical challenges”. The extensive presence of high-rise buildings obstructs the widespread adoption of renewable energy sources, which can be identified as a fundamental cause for the limited implementation of renewable energy and is categorized as a “technical challenge”. Similarly, ‘*obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)*’ directly impact the implementation of “renewable energy” technologies for prevailing residential buildings. Accordingly, it is evident that “geographical challenges” notably impact “technical challenges”, which have been identified as the most significantly influenced challenge to residential building NZC retrofitting.

‘*Obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)*’ and ‘*difficulties due to high-rise, high-density urban environment*’ were the key factors that influenced “geographical challenges”. The widespread presence of numerous high-rise buildings and high levels of urbanization pose significant challenges in the implementation of renewable energy sources within developed regions. This factor may serve as a primary justification for the limited adoption of renewable energy sources in domestic activities. Furthermore, this situation underscores the interconnectedness between the factors of “geographical challenges”.

In light of the factors influencing the "geographical challenges" associated with retrofitting residential buildings toward achieving the NZC state, Hong Kong should prioritize the optimal utilization of land for the generation of energy from renewables as a means to realize an NZC-built environment. This emphasis is warranted due to the distinct geographical attributes of Hong Kong, as highlighted by Pan and Pan (2019), which include the prevalence of high-rise buildings, high population density, and a hot and humid urban environment. These characteristics pose significant obstacles in the pursuit of zero-carbon buildings. Consequently, tailored strategies and approaches specific to the contextual needs of Hong Kong must be developed to effectively retrofit the substantial existing residential building stock and achieve NZC buildings.

5.6 Chapter Summary, Contributions, and Limitations

This chapter undertook a quantitative analysis to examine the challenges impeding the retrofitting of existing residential buildings toward achieving NZC, with a specific focus on the perspective of building occupants. This chapter attempts to identify critical challenges and to assess the relationships among those challenges by employing a hypothetical model to evaluate their impact on the NZC retrofitting of residential buildings. To gather data, a questionnaire survey was done among the building occupants in Hong Kong, resulting in 123 responses, which were subsequently analyzed employing "PLS-SEM".

The findings of the analysis indicated that "*obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)*", "*difficulties due to high-rise, high-density urban environments*", and "*lack of knowledge and awareness on retrofitting*" as the first three critical challenges based on the mean score ranking method. Further, among the six challenge categories, "social challenges" and "technical challenges" had a significant impact on residential building NZC retrofitting as per PLS-SEM analysis. "Technical challenges" were measured by two indicators; '*lack of data and information*' and '*lack of widespread adoption of energy efficiency, renewable, and smart technologies*' while "social challenges" were measured by four indicators; '*doubts regarding energy savings*', '*resistance to change*', '*lack of knowledge and awareness on retrofitting*', and '*unwillingness to invest in retrofitting*'. From these two categories "technical challenges" emerged as the most influential challenges in residential building NZC retrofitting. Additionally, paths connecting "industrial and stakeholder challenges" to "social challenges", "financial challenges" to "administrative challenges", and "geographical challenges" to "technical challenges" were supported at a 0.05 significant level while paths connecting "administrative challenges" to "social challenges", "geographical challenges" to "administrative challenges", "technical challenges" to "financial challenges", "administrative challenges" to "industrial and stakeholder challenges", "geographical challenges" to "industrial and stakeholder challenges", and "technical challenges" to "industrial and stakeholder challenges" were supported at a 0.01 significant level.

According to the findings, "geographical challenges" were identified as a driving force behind the emergence of "technical challenges" while "administrative challenges" and "industrial and stakeholder challenges" were the driving forces behind the emergence of "social challenges". Even though "financial challenges" did not significantly influence residential building NZC, they had a significant influence on "administrative challenges", which were identified as a driving force to "social challenges". Accordingly, all those challenges directly or indirectly influenced residential building NZC retrofitting. However, addressing "technical challenges" becomes crucial in order to mitigate their impact on NZC retrofitting efforts for prevailing residential buildings. Additionally, this chapter provides suggestions to overcome the identified challenges when discussing the interconnections among different challenge categories.

The theoretical involvement of this chapter includes the identification of challenges specific to NZC retrofitting of existing residential buildings, while practical implications involve the recognition of significant challenges that necessitate consideration prior to embarking on NZC retrofitting. These findings offer guidance to policymakers in formulating strategies to address the challenges associated with NZC retrofitting, as well as in developing plans to achieve NZC residential buildings within Hong Kong and other regions globally. Moreover, the outcomes of this chapter could contribute to an enhanced comprehension of the key challenges that declare attention when advocating for the development of residential building NZC retrofitting. By shedding light on these challenges, the current chapter makes substantial support to the broader corpus of knowledge on NZC retrofitting practices worldwide.

The chapter is subject to several limitations that should be acknowledged. Firstly, the data gathering was limited to Hong Kong. Secondly, the study concentrated mainly on residential buildings and the building occupants. Furthermore, the employed mean score ranking method and PLS-SEM approach do not incorporate the dynamic aspects of NZC residential building retrofitting challenges. Consequently, upcoming research could apply the CB-SEM technique to validate the outcomes of the current chapter or explore alternative analytical approaches. Additionally, future research endeavors could consider utilizing "system dynamic modeling" methodologies to compensate for the dynamic nature of challenges inherent in the NZC retrofitting of existing residential buildings. Further, future research efforts should focus on improving decision-making models that incorporate simulation and life cycle assessment tools to demonstrate the impact of alternative retrofit strategies on achieving NZC residential buildings. These models would be critical in resolving challenges, allowing for the selection of optimized retrofit solutions based on carbon emissions, retrofitting costs, and occupant satisfaction. Such models would have the potential to mitigate the challenges and streamline decision-making processes in residential building retrofitting by motivating occupants to perform retrofitting aimed at meeting NZC.

CHAPTER SIX[6]

6.0 Analysis and Modeling of the Relationship between Measures to Retrofit Residential Buildings Toward NZC

6.1 Introduction

Chapter 5 analyzes the challenges of residential building NZC retrofitting in Hong Kong, while the current chapter analyzes the measures used to retrofit residential buildings towards NZC. This chapter is developed based on the findings from two questionnaire surveys; (1) with building occupants, and (2) with experts. The details of the respondents for both surveys were detailed in Tables 3.6 and 3.7. This chapter attempts to prioritize the retrofit measures based on building occupant's perspectives, to identify the importance of identified retrofit measures, and to model the relationship between retrofitting measures. To achieve this, the literature findings in section 2.2.3 were used for the questionnaire surveys. Building occupants were asked to arrange the retrofit measures categories according to their preferences to assess their opinions on retrofit types. In addition, experts were asked to rate the importance of different retrofit measures using a five-point Likert scale; 1- not important, 2 - less important, 3 - neutral, 4 - important, and 5 - very important.

The findings from the survey with building occupants were subjected to the Friedman test using the SPSS package to evaluate the preferences of building occupants with different measure types. The findings from the survey with experts were subjected to statistical tests using the SPSS package. After completing the statistical tests, PLS-SEM was used to quantitatively evaluate retrofit measures useful in developing retrofit strategies. Accordingly, the current

[6] This chapter has been partially published in Weerasinghe, L.N.K., Darko, A., and Chan, A.P.C. (2024, February). Net zero carbon retrofitting of existing buildings – A bibliometric study. In 14th International Conference on Industrial Engineering and Operations Management.

chapter aims to explore and quantitatively model the appropriateness of numerous retrofitting measures associated with the building envelope, energy systems, and renewable energy upgrades on attaining NZC status in residential buildings, particularly within Hong Kong. Hence, this chapter provides information necessary to improve the building retrofitting towards NZC by ensuring the building occupant's preferences. Further, the results of this chapter would guide decision-makers in selecting the most significant measures for retrofitting residential buildings by contributing to achieving net-zero status by the year 2050.

6.2 Building Occupant's Preferences Toward Net Zero Carbon Retrofit Measures

6.2.1 Results of Friedman Test

The building occupants have ranked the retrofit measure types under building envelope upgrades, energy system upgrades, and renewable energy upgrades according to their preferences, where 1 is given for the most preferred measure. The results of the Friedman test following the mean score ranking method are illustrated in Table 6.1, while the statistical test of the Friedman criterion is illustrated in Table 6.2.

Table 6.1: Ranking of categories of NZC retrofitting measures using the Friedman test.

Category of Measures	Mean Rank	Rank	Subcategories	Mean Rank	Rank
Renewable energy	1.43	1	Solar energy	1.05	1
			Wind energy	1.95	2
Energy system	1.91	2	Lighting system retrofitting	1.64	1
			HVAC system retrofitting	2.42	2
			Hot water system retrofitting	3.05	3
Building envelope	2.66	3	Wall retrofitting	1.94	1
			Window retrofitting	2.52	2
			Roof retrofitting	3.00	3
			Door retrofitting	3.32	4
			Floor retrofitting	4.21	5

Table 6.2: The statistical test of Friedman criterion.

Analyzed Measures	Chi-Square	Degree of Freedom	Asymptotic Significance
Main categories of measures	94.193	2	<0.001
Renewable energy upgrade categories	100.171	1	<0.001
Energy system upgrade categories	88.416	3	<0.001
Building envelope upgrade categories	143.728	4	<0.001

According to Table 6.1, there is a significant difference between the preferences of building occupants towards the different types of retrofitting measures. In addition, Table 6.2 shows that the results are significant by having $p < 0.005$, where the null hypothesis can be rejected.

Results demonstrated that building occupants mostly prefer to adopt renewable energy sources to retrofit the existing residential buildings towards NZC. In relation to different categories of retrofitting measures, building occupants are most preferred for solar energy retrofitting, lighting system retrofitting, and wall retrofitting, as renewable energy, energy system, and building envelope retrofitting, respectively. Further rankings of the building occupant's preferences for the retrofitting measures are illustrated in Table 6.1.

6.2.2 Discussion of Results

According to the global NZC standards, their golden rule of achieving net zero is prioritizing the energy-efficient measures that support reducing the energy demand of buildings (WGBC, 2024). However, this study's results represent a surprising finding, indicating the preferences of occupants leaned towards renewable energy sources rather than energy systems and building envelope retrofitting. This inclination may arise from the perceived feasibility of installing a renewable energy source compared to the complexities associated with retrofitting the energy systems and building envelope in Hong Kong's building stock (Li et al., 2017). Additionally, the adoption of renewable energy sources is seen as crucial for meeting NZC targets, serving to offset the carbon balance resulting from the embodied carbon of retrofitting materials (UKGBC, 2019). Furthermore, the findings indicated that among the renewable energy options, occupants predominantly favored retrofitting with solar energy as opposed to wind energy. Comparatively low cost for installation and maintenance makes solar panels the most preferred renewable energy source among building occupants (REGENpower, 2024). Further, due to the limitations on space, building occupants are reluctant to employ wind energy as a renewable energy source. This preference aligns with the significance and efficacy of solar energy sources highlighted by Heidari et al. (2022) in the context of achieving NZC targets. Consequently, the results suggested that occupants exhibit a stronger preference for retrofitting existing residential buildings with solar energy sources compared to other energy-efficient measures.

Regarding retrofitting measures pertaining to energy systems, occupants displayed a strong preference for lighting system retrofitting. This preference can be attributed to the perceived lower cost and complexity associated with retrofitting lighting systems compared to other energy system retrofitting measures. In comparison to retrofitting HVAC systems and hot water systems, occupants may find it relatively easier to make changes to their lighting systems by adjusting luminous levels and controlling the use of lights within the building. Such adjustments contribute to reducing energy consumption, which directly impacts carbon emissions. Consequently, when devising innovative strategies to decrease carbon emissions from existing residential buildings through energy system management, it is advisable to prioritize lighting energy retrofitting. This recommendation stems from the high level of preference expressed by occupants toward retrofitting lighting systems over other energy systems.

Among the various building envelope retrofitting options, occupants have shown a predominant preference for wall and window retrofitting, while floor retrofitting is considered the least favored. Given that Hong Kong primarily consists of multi-unit residential apartment buildings, retrofitting the envelope of individual residential units poses significant challenges. (Kermanshahi et al., 2020) showed similar results from a quantitative analysis conducted based on Malaysian building occupant preferences. Even in a developing region, they experienced window and wall retrofitting measures as most favorable mentioning building complexity and less disruption to the building occupants from wall and window retrofitting. However, walls represent the outermost layer of residential units, making wall retrofitting comparatively more feasible than retrofitting the floor, roof, doors, and windows. Elsayed et al. (2023) further explained that building occupants select wall and window retrofitting due to their affordable prices compared with other components, through a study conducted focusing on building occupants in Italy. Moreover, Wang et al. (2022) emphasized that wall retrofitting measures and solar energy integration are necessary for achieving zero-carbon building in the United Kingdom, through a study conducted considering building owners as the target population in developing cost-optimal retrofit strategies. Boeri et al. (2016) have proposed the implementation of green facades, such as vegetation on walls, as a means to offset carbon emissions from existing buildings and facilitate their transition to NZC status. Nonetheless, it is advisable to introduce additional wall retrofitting measures that can be easily implemented, thereby mitigating the complexities associated with retrofitting residential units. Such measures would contribute to achieving NZC targets for existing residential buildings.

6.3 Testing the Importance of Identified Measures for Residential Building NZC Retrofitting

The retrofit measures identified through the literature review and pilot survey were used to develop the questionnaire to distribute among experts in the domain of residential building NZC retrofitting. Finally, 45 retrofit measures were identified (Table 6.3) under building envelop upgrades, energy system upgrades, and renewable energy upgrades, and respondents were asked to rate the importance of those measures using 1- not important, 2 - less important, 3 - neutral, 4 - important, and 5 - very important. Before assessing the importance of these measures, data reliability and normality tests were checked using the SPSS package. The 0.946 value of Cronbach's alpha coefficient from the reliability test confirmed the reliability of the data while p-values below 0.05 from the Shapiro-Wilk test confirmed the non-normal distribution of data. Finally, one sample t-test and mean scores were calculated to assess the importance of identified measures. Table 6.3 represents the mean scores of retrofit measures.

Table 6.3: Mean scores of retrofit measures identified to achieve NZC residential buildings.

Retrofitting category	Measure type	Measures	Mean
Building envelope upgrades	Roof retrofitting	Ceiling insulation	3.94
		Implementation of roof plastering with low solar absorptance	3.58
		Apply a layer of black high-density polyethylene (HDPE) net with 90% shading as a roof cover	3.54
		Apply vegetation	3.54
		Add insulation	3.50
		Apply cement tile or light-colored linoleum-pressed steel sheet	3.13
	Wall retrofitting	Add insulations	3.98
		Apply shadings	3.83
		Green facade	3.69
		Apply thermal plasters	3.67
		Facade insulations	3.56
		Aerogel plaster on the external wall	3.31
		Adding vapor barriers to the facade	3.29
	Window retrofitting	Install triple-glazed widows	4.00
		Use of energy-efficient glazing (low e values)	3.87
		Sealings of windows and joint places	3.75
		Install double-glazed windows	3.54
		Adjust window to wall ratio	3.50
		Install automatic shading devices above the windows	3.42
		Apply thin film coating on the windows	3.42
		Fill argon gas between two layers of glass	3.27
		Use PVC window frame with double glazing	3.23
		Use polyvinylchloride PVC window frame with triple glazing	3.17
		Dynamic window replacement module, which includes automated solar-tracking blinds for shading control with night insulation properties	3.13
		Replace windows with low U-value windows	3.10
	Door retrofitting	Replace with new energy-efficient doors	3.50
		Use double-glazed doors	3.21
		Upgrade double-glazed PVC units with air-filled gaps	3.08
	Floor retrofitting	Add insulation	4.08
		Upgrade floor finishes and coverings	3.25
Energy system upgrades	HVAC system retrofitting	Apply new central heating systems	4.04
		Use of efficient heat pumps	3.98
		Update the entire HVAC system	3.96
		Adjust the heating and cooling set point in an efficient way	3.85
		Use a ventilation system with heat recovery ventilation	3.75
		Use high-efficiency boilers and cooling sources	3.15

	Lighting system retrofitting	Control the lighting level and equipment operation	4.27
		Improve natural ventilation and lighting	4.17
		Replacement of light bulbs with efficient bulbs	3.90
	Hot water system	Use an electric water heater	3.58
		Install a domestic hot water system	3.54
Renewable energy upgrades	Solar energy	Install solar thermal collectors	3.90
		Install PV panels	3.75
	Wind energy	Use wind wind-assisted ventilation system	4.10
		Install wind turbine	3.17

As per the data presented in Table 6.3, the mean score ratings of the retrofit measures fall within the range of 3.08 to 4.17. The analysis suggests that all these measures hold substantial significance in the pursuit of NZC residential buildings, given that their mean scores surpass 3.00, representing the midpoint of the rating scale. Furthermore, the statistical significance evidenced by p-values below 0.05 in the one-sample t-test indicates that all measures listed in Table 6.3 make significant contributions towards the realization of NZC residential buildings. Accordingly, all these measures were used in the PLS-SEM analysis to model their relationships with the residential building NZC retrofitting.

6.4 Research Framework

A framework serves as a valuable tool for advancing knowledge (Jayasena et al., 2024). In terms of achieving NZC buildings, the UKGBC has introduced frameworks for both constructing and retrofitting buildings to NZC. The UKGBC emphasizes the need to lower existing building's operational carbon releases to zero or negative levels to achieve NZC status (UKGBC, 2019). Given that energy consumption is a significant source of carbon emissions in existing buildings (Besana & Tirelli, 2022), reducing operational energy-related emissions becomes crucial for NZC achievement. According to the literature findings detailed in section 2.2.3, the retrofit measures used to reduce the operational carbon emissions can be identified as energy saving measures and energy supply measures (renewable energy). In addition, researchers have identified those measures as passive and active measures (D'Agostino et al., 2021; El-Sherif et al., 2020) while some have categorized them as minor, major, and deep retrofit measures based on their energy saving capacities (Ruparathna et al., 2017). However, collective contributions from both energy saving and renewable energies are essential in achieving the NZC residential buildings (Weerasinghe et al., 2024). The UKGBC framework also features the significance of incorporating sources from renewable energy to balance energy consumption, improving energy performance, and offset remaining carbon emissions. Therefore, this study identified the measures to achieve NZC residential buildings as measures to building envelope, energy system, and renewable energy upgrades, since it covered all the technical retrofit measures that can be physically implemented on residential buildings to achieve NZC. Building upon those theories, the study proposes a framework (Figure 6.1) that establishes connections between retrofitting measures and NZC residential buildings. This framework facilitates the identification and implementation of various retrofitting measures necessary for achieving NZC residential buildings. The framework categorizes retrofitting measures into envelope upgrades, energy system upgrades, and renewable energy sources, all of which are essential for NZC attainment. The positive sign (+) in the framework signifies the interdependence and collective impact of these measures in achieving NZC residential buildings. Further, the outcomes of the framework would support the development of retrofit strategies to achieve NZC residential buildings. Therefore, analyzing these three types of measures simultaneously is appropriate, as they work together to achieve the desired NZC residential buildings.

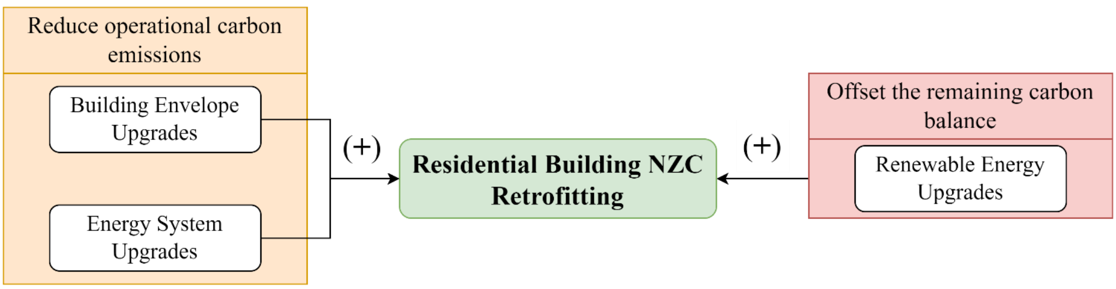


Figure 6.1: Research framework.

6.5 Hypotheses Development

This chapter focuses on the evaluation of retrofitting measures for achieving NZC status in residential buildings, with a specific emphasis on three key areas: (1) building envelope upgrades, (2) energy system upgrades, and (3) renewable energy upgrades. Given the pressing global challenge of climate variation and significant carbon releases attributed to residential buildings, the conversion of existing residential buildings to NZC becomes imperative in enhancing sustainability within the construction industry. During the initial stage of this research project, 45 measures that can be used to retrofit residential buildings towards NZC were discovered after a comprehensive literature analysis. As a result of the literature findings and suggestions from the pilot survey, a total of 30 measures were identified for building envelope upgrades, which were further classified into five distinct groups: window retrofitting, roof retrofitting, wall retrofitting, door retrofitting, and floor retrofitting. Additionally, 11 measures were identified for energy system upgrades: HVAC system retrofitting, hot water system retrofitting, and lighting system retrofitting. Furthermore, the study identified three specific measures related to the integration of solar energy and wind energy as renewable energy upgrades. Identifying and employing appropriate measures could significantly help to encourage the residential building NZC retrofitting.

Table 6.4 shows the 10 constructs, specifically the constructs concerning building envelope, energy system, and renewable energy upgrades as well as their corresponding measurement items, which have been adjusted in the current study to select the most suitable retrofit measures under “building envelope”, “energy system”, and “renewable energy” upgrades on achieving NZC in existing residential buildings. Residential building retrofitting to NZC is a great achievement in the building sector since it could help combat climate change issues. In addition, numerous benefits can be gained from the residential building NZC retrofitting as per the review by Weerasinghe et al. (2024). Therefore, the current study used the benefits as indicated in Table 6.4 to measure the residential building NZC retrofitting.

Table 6.4: Constructs with its associated measurement items.

Constructs	Code	Measurement items
		Building Envelope Upgrades
Roof retrofitting (RR)	RR1	Ceiling insulation
	RR2	Implementation of roof plastering with low solar absorptance
	RR3	Apply a layer of black high-density polyethylene (HDPE) net with 90% shading as a roof cover
	RR4	Apply vegetation
	RR5	Add insulation
	RR6	Apply cement tile or light-colored linoleum-pressed steel sheet
Wall retrofitting (WR)	WR1	Add insulations
	WR2	Apply shadings
	WR3	Green facade
	WR4	Apply thermal plasters
	WR5	Facade insulations
	WR6	Aerogel plaster on the external wall
	WR7	Adding vapor barriers to the facade
Window retrofitting (CR)	CR1	Install triple-glazed widows
	CR2	Use of energy-efficient glazing (low e values)
	CR3	Sealings of windows and joint places
	CR4	Install double-glazed windows
	CR5	Adjust window to wall ratio
	CR6	Install automatic shading devices above the windows
	CR7	Apply thin film coating on the windows
	CR8	Fill argon gas between two layers of glass
	CR9	Use PVC window frame with double glazing
	CR10	Use polyvinylchloride PVC window frame with triple glazing
	CR11	Dynamic window replacement module, which includes automated solar-tracking blinds for shading control with night insulation properties
	CR12	Replace windows with low U-value windows
Door retrofitting (DR)	DR1	Replace with new energy-efficient doors
	DR2	Use double-glazed doors
	DR3	Upgrade double-glazed PVC units with air-filled gaps
Floor retrofitting (FR)	FR1	Add insulation
	FR2	Upgrade floor finishes and coverings
		Energy System Upgrades
HVAC system retrofitting (HVACSR)	HVACR1	Apply new central heating systems
	HVACR2	Use of efficient heat pumps
	HVACR3	Update the entire HVAC system
	HVACR4	Adjust the heating and cooling set point in an efficient way
	HVACR5	Use a ventilation system with heat recovery ventilation
	HVACR6	Use high-efficiency boilers and cooling sources
Lighting system retrofitting (LSR)	LSR1	Control the lighting level and equipment operation
	LSR2	Improve natural ventilation and lighting

	LSR3	Replacement of light bulbs with efficient bulbs
Hot water system (HWSR)	HWSR1	Use an electric water heater
	HWSR2	Install a domestic hot water system
	Renewable Energy Upgrades	
Solar energy (SE)	SE1	Install solar thermal collectors
	SE2	Install PV panels
Wind energy (WE)	WE1	Use wind-assisted ventilation system
	WE2	Install wind turbine
	Residential Building NZC Retrofitting	
Residential building NZC retrofitting (NZCR)	NZCR1	Lower the building maintenance costs
	NZCR2	Increase the building value
	NZCR3	Increased accessibility to incentives and subsidies
	NZCR4	Reduced energy costs
	NZCR5	Reduced environmental pollution
	NZCR6	Reduced energy consumption, energy saving, and secured energy supply
	NZCR7	Reduced CO_2 and GHG emissions
	NZCR8	Minimizing adverse climatic effects
	NZCR9	Improved building comfort (thermal, natural, lighting, acoustic, etc.)
	NZCR10	Increased the efficiency and reliability of the building system
	NZCR11	Increased building usable time
	NZCR12	Increased indoor and outdoor air quality

Drawing upon the outcomes from the literature analysis, it is evident that building envelope and energy system upgrades contribute to the decrease of operational carbon releases within residential buildings. Furthermore, these upgrades reduced the energy demand by minimizing the initial investment required for renewable energy sources to attain NZC buildings. Consequently, building envelope upgrades and energy system upgrades exert a positive influence on the NZC retrofitting of residential buildings. Additionally, the integration of energy from renewable sources performs an essential part in offsetting the remaining carbon emissions arising from operational energy consumption. Thus, renewable energy upgrades also exhibit a positive impact on the NZC retrofitting of residential buildings. Based on the literature results and the study framework illustrated in Figure 6.1, the subsequent hypotheses have been suggested.

H1a – Door retrofitting-related measures are appropriate for residential building NZC retrofitting.

H1b – Floor retrofitting-related measures are appropriate for residential building NZC retrofitting.

H1c – Roof retrofitting-related measures are appropriate for residential building NZC retrofitting.

H1d – Wall retrofitting-related measures are appropriate for residential building NZC retrofitting.

H1e – Window retrofitting-related measures are appropriate for residential building NZC retrofitting.

H2a – HVAC system retrofitting-related measures are appropriate for residential building NZC retrofitting.

H2b – Hot water system retrofitting-related measures are appropriate for residential building NZC retrofitting.

H2c – Lighting system retrofitting-related measures are appropriate for residential building NZC retrofitting.

H3a – Solar energy-related retrofitting measures are appropriate for residential building NZC retrofitting.

H3b – Wind energy-related retrofitting measures are appropriate for residential building NZC retrofitting.

Figure 6.2 was formulated by integrating the hypotheses, which are comprehensively examined in this study to enhance the knowledge of retrofitting measures aimed at transforming residential buildings into NZC. The outcomes of this analysis are anticipated to provide important guidance for practitioners and policymakers, facilitating the advancement of NZC retrofitting practices and thereby promoting the sustainability of the construction industry.

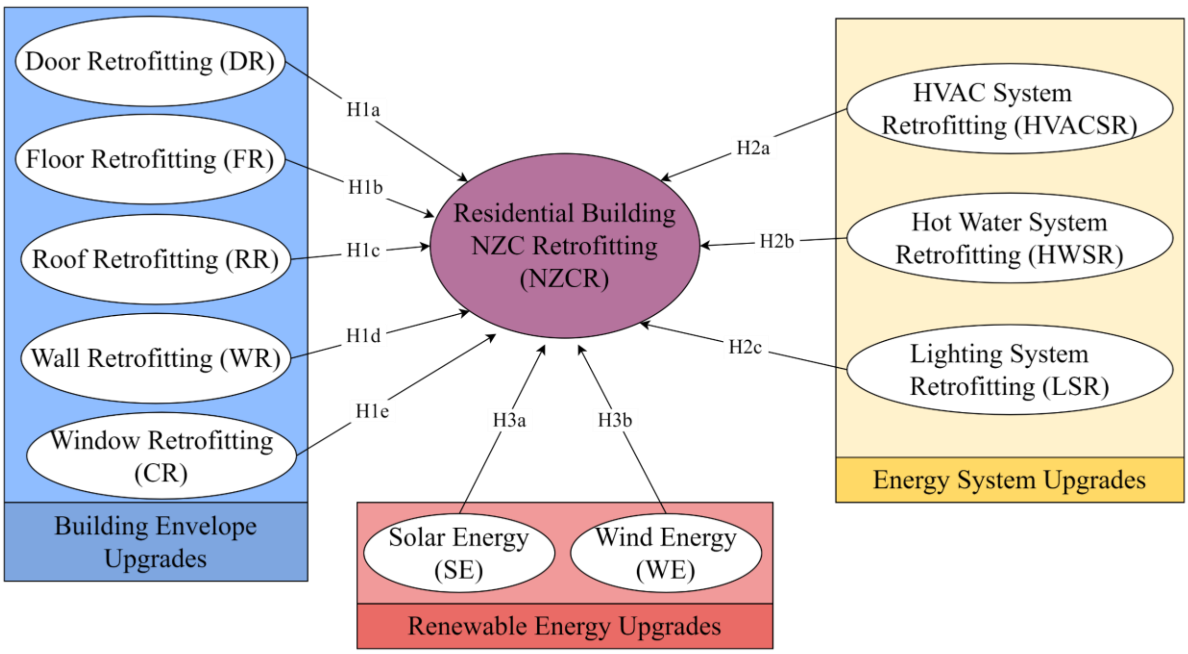


Figure 6.2: Hypothetical model for the measures used to retrofit residential buildings to NZC.

6.6 PLS-SEM Results

6.6.1 Building Envelope Upgrades

6.6.1.1 Evaluation of Measurement Model

Measurement items, RR1, RR2, RR4, WR1, WR3, WR4, CR1, CR2, CR4, CR7, CR8, NZCR2, NZCR3, NZCR8, NZCR10, and NZCR11 were omitted from the analysis since their factor loadings below the threshold of 0.5. Table 6.5 presents the measurement items employed to measure reliability and convergent validity. Apart from the aforementioned observations, the interpretations regarding the results in Tables 6.6-6.8 align with the interpretations presented in section 4.5.1.

Table 6.5: Evaluation of measurement model for building envelope upgrades.

Construct	Measurement item	Factor loading	Cronbach's alpha	Composite reliability	AVE
Door retrofitting	DR1	0.833	0.870	0.921	0.795
	DR2	0.881	-	-	-
	DR3	0.958	-	-	-
Floor retrofitting	FR1	0.925	0.865	0.936	0.880
	FR2	0.951	-	-	-
Roof retrofitting	RR3	0.838	0.762	0.859	0.670
	RR5	0.768	-	-	-
	RR6	0.847	-	-	-
Wall retrofitting	WR2	0.797	0.807	0.874	0.634
	WR5	0.717	-	-	-
	WR6	0.806	-	-	-
	WR7	0.859	-	-	-
Window retrofitting	CR3	0.767	0.866	0.898	0.659
	CR5	0.582	-	-	-
	CR6	0.760	-	-	-
	CR9	0.767	-	-	-
	CR10	0.821	-	-	-
	CR11	0.816	-	-	-
	CR12	0.691	-	-	-
Residential building NZC retrofitting	NZCR1	0.775	0.900	0.922	0.628
	NZCR4	0.775	-	-	-
	NZCR5	0.666	-	-	-
	NZCR6	0.870	-	-	-
	NZCR7	0.813	-	-	-
	NZCR9	0.773	-	-	-
	NZCR12	0.860	-	-	-

Table 6.6: Results of Fornell and Larcker criterion for building envelope upgrades.

	Door retrofitting	Floor retrofitting	Roof retrofitting	Wall retrofitting	Window retrofitting	Residential building NZC retrofitting
Door retrofitting	**0.892**					
Floor retrofitting	0.214	**0.938**				
Roof retrofitting	0.629	0.477	**0.818**			
Wall retrofitting	0.418	0.475	0.480	**0.796**		
Window retrofitting	0.473	0.623	0.673	0.638	**0.812**	
Residential building NZC retrofitting	0.474	0.605	0.624	0.680	0.747	**0.793**

Table 6.7: HTMT ratio values for building envelope upgrades.

	Door retrofitting	Floor retrofitting	Roof retrofitting	Wall retrofitting	Window retrofitting	Residential building NZC retrofitting
Door retrofitting						

Floor retrofitting	0.237				
Roof retrofitting	0.760	0.555			
Wall retrofitting	0.480	0.558	0.592		
Window retrofitting	0.558	0.714	0.827	0.763	
Residential building NZC retrofitting	0.522	0.677	0.713	0.786	0.813

Table 6.8: Cross-loading values for building envelope upgrades.

	Door retrofitting	Floor retrofitting	Roof retrofitting	Wall retrofitting	Window retrofitting	Residential building NZC retrofitting
DR1	**0.833**	0.154	0.572	0.336	0.373	0.379
DR2	**0.881**	0.177	0.487	0.298	0.380	0.365
DR3	**0.958**	0.232	0.613	0.460	0.495	0.504
FR1	0.146	**0.925**	0.406	0.441	0.542	0.505
FR2	0.246	**0.951**	0.483	0.450	0.620	0.620
RR3	0.524	0.510	**0.838**	0.367	0.605	0.626
RR5	0.438	0.308	**0.768**	0.300	0.469	0.370
RR6	0.571	0.305	**0.847**	0.505	0.552	0.478
WR2	0.289	0.321	0.286	**0.797**	0.435	0.488
WR5	0.175	0.426	0.302	**0.717**	0.440	0.518
WR6	0.395	0.283	0.391	**0.806**	0.463	0.469
WR7	0.448	0.454	0.514	**0.859**	0.653	0.658
CR3	0.491	0.556	0.485	0.555	**0.767**	0.614
CR5	0.501	0.322	0.571	0.570	**0.582**	0.435
CR6	0.218	0.459	0.360	0.490	**0.760**	0.613
CR9	0.305	0.350	0.399	0.520	**0.767**	0596
CR10	0.186	0.483	0.547	0.461	**0.821**	0.713
CR11	0.475	0.512	0.553	0.418	**0.816**	0.642
CR12	0.381	0.554	0.634	0.379	**0.691**	0.595
NZCR1	0.352	0.467	0.507	0.470	0.640	**0.775**
NZCR4	0.299	0.388	0.339	0.592	0.570	**0.775**
NZCR5	0.411	0.501	0.437	0.620	0.610	**0.666**
NZCR6	0.302	0.437	0.421	0.614	0.661	**0.870**
NZCR7	0.313	0.572	0.449	0.404	0.689	**0.813**
NZCR9	0.504	0.402	0.758	0.471	0.619	**0.773**
NZCR12	0.414	0.568	0.503	0.594	0.694	**0.860**

6.6.1.2 Evaluation of Structural Model

After validating the measurement model, the evaluation of the structural model commenced utilizing bootstrapping with 5000 subsamples. The outcomes of the structural model evaluation are illustrated in Figure 6.3, presenting the path coefficients and corresponding t-values. The path coefficients from building envelope upgrades to residential building NZC retrofitting indicate positive attributes, aligning with the formulated hypotheses. The effect of independent variables on dependent variables can vary depending on the magnitude of the path coefficients

(Aibinu & Al-Lawati, 2010). Consequently, supported hypotheses H1d and H1e exert a high and weak appropriateness for residential building NZC retrofitting. Furthermore, the t-values in Table 6.9 show that hypotheses H1a, H1b, and H1c are not supported due to t-values less than 1.65, 1.96, and 2.58. The hypotheses H1d and H1e were significant at the 0.05 and 0.01 levels due to their t-values surpassing 1.96 and 2.58 respectively.

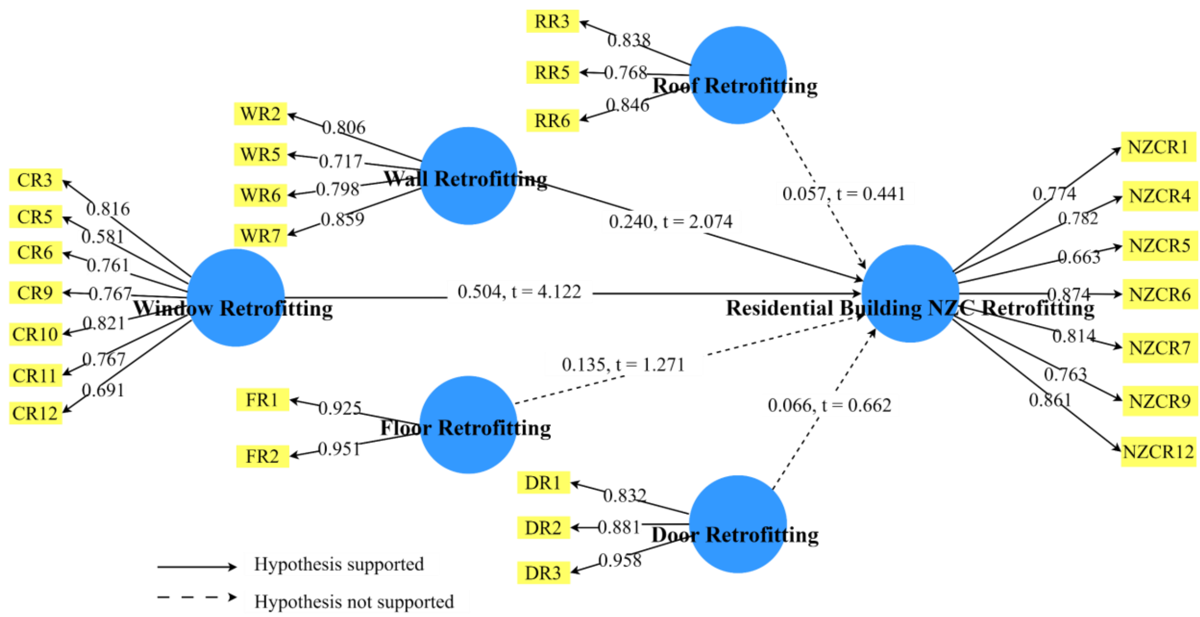


Figure 6.3: Structural model for building envelope upgrades.

Table 6.9: Hypotheses results for building envelope upgrades.

Hypothesis number	Hypotheses	Path coefficient	t-value	p-value	Decision
H1a	Door retrofitting -> Residential building NZC retrofitting	0.066	0.662	0.508	Hypothesis not supported
H1b	Floor retrofitting -> Residential building NZC retrofitting	0.135	1.271	0.204	Hypothesis not supported
H1c	Roof retrofitting -> Residential building NZC retrofitting	0.057	0.441	0.659	Hypothesis not supported
H1d	Wall retrofitting -> Residential building NZC retrofitting	0.240	2.074	0.038	Hypothesis supported
H1e	Window retrofitting -> Residential building NZC retrofitting	0.504	4.122	0.000	Hypothesis supported

6.6.2 Energy System Upgrades

6.6.2.1 Evaluation of Measurement Model

The measurement items HVACR3, NZCR4, NZCR5, NZCR9, NZCR10, and NZCR11 were eliminated due to their factor loading values falling below 0.5 in order to maintain the model's reliability and validity. The outcomes of the measurement model evaluation are presented in Table 6.10. Apart from the aforementioned observations, the interpretations regarding the results in Tables 6.11-6.13 align with the interpretations presented in section 4.5.1

Table 6.10: Evaluation of measurement model for energy system upgrades.

Construct	Measurement item	Factor loading	Cronbach's alpha	Composite reliability	AVE
HVAC system retrofitting	HVACSR1	0.787	0.863	0.901	0.647
	HVACSR2	0.759	-	-	-
	HVACSR4	0.829	-	-	-
	HVACSR5	0.838	-	-	-
	HVACSR6	0.806	-	-	-
Hot water system retrofitting	HWSR1	0.950	0.865	0.936	0.880
	HWSR2	0.925	-	-	-
Lighting system retrofitting	LSR1	0.919	0.967	0.978	0.936
	LSR2	0.993	-	-	-
	LSR3	0.988	-	-	-
Residential building NZC retrofitting	NZCR1	0.775	0.900	0.922	0.634
	NZCR2	0.757	-	-	-
	NZCR3	0.657	-	-	-
	NZCR6	0.873	-	-	-
	NZCR7	0.828	-	-	-
	NZCR8	0.774	-	-	-
	NZCR12	0.865	-	-	-

Table 6.11: Results of Fornell and Larcker criterion for energy system upgrades.

	HVAC system retrofitting	Hot water system retrofitting	Lighting system retrofitting	Residential building NZC retrofitting
HVAC system retrofitting	**0.804**			
Hot water system retrofitting	0.588	**0.938**		
Lighting system retrofitting	0.165	0.087	**0.967**	
Residential building NZC retrofitting	0.693	0.609	0.109	**0.796**

Table 6.12: HTMT ratio values for energy system upgrades.

	HVAC system retrofitting	Hot water system retrofitting	Lighting system retrofitting	Residential building NZC retrofitting
HVAC system retrofitting				
Hot water system retrofitting	0.674			
Lighting system retrofitting	0.173	0.102		
Residential building NZC retrofitting	0.895	0.677	0.115	

Table 6.13: Cross-loading values for energy system upgrades.

	HVAC system retrofitting	Hot water system retrofitting	Lighting system retrofitting	Residential building NZC retrofitting
HVACSR1	**0.787**	0.459	0.058	0.614
HVACSR2	**0.759**	0.556	0.021	0.619
HVACSR4	**0.829**	0.512	0.212	0.642
HVACSR5	**0.838**	0.483	0.229	0.714
HVACSR6	**0.806**	0.350	0.125	0.603
HWSR1	0.600	**0.950**	0.068	0.623
HWSR2	0.494	**0.925**	0.099	0.510
LSR1	0.104	0.109	**0.919**	0.064
LSR2	0.176	0.082	**0.993**	0.115
LSR3	0.176	0.075	**0.988**	0.121
NZCR1	0.609	0.467	0.174	**0.775**
NZCR2	0.563	0.402	0.103	**0.757**
NZCR3	0.597	0.501	0.074	**0.657**
NZCR6	0.654	0.436	0.114	**0.873**
NZCR7	0.711	0.572	0.117	**0.828**
NZCR8	0.540	0.387	0.035	**0.774**
NZCR12	0.704	0.568	-0.008	**0.865**

6.6.2.2 Analysis of Structural Model

The outcomes of the structural model evaluation are presented in Table 6.14, while Figure 6.4 visually depicts the final structural model, showcasing the path coefficients and corresponding t-values. H2a and H2b were supported at significant levels of 0.01 and 0.05, as evidenced by t-values exceeding 2.58 and 1.96, respectively (Table 6.14). Hypothesis H2a, which pertains to the pathway connecting HVAC system retrofitting to residential building NZC retrofitting, exhibited the highest path coefficient, indicating its higher suitability, while the path connecting hot water system retrofitting to residential building NZC retrofitting (H2b) demonstrates less suitability.

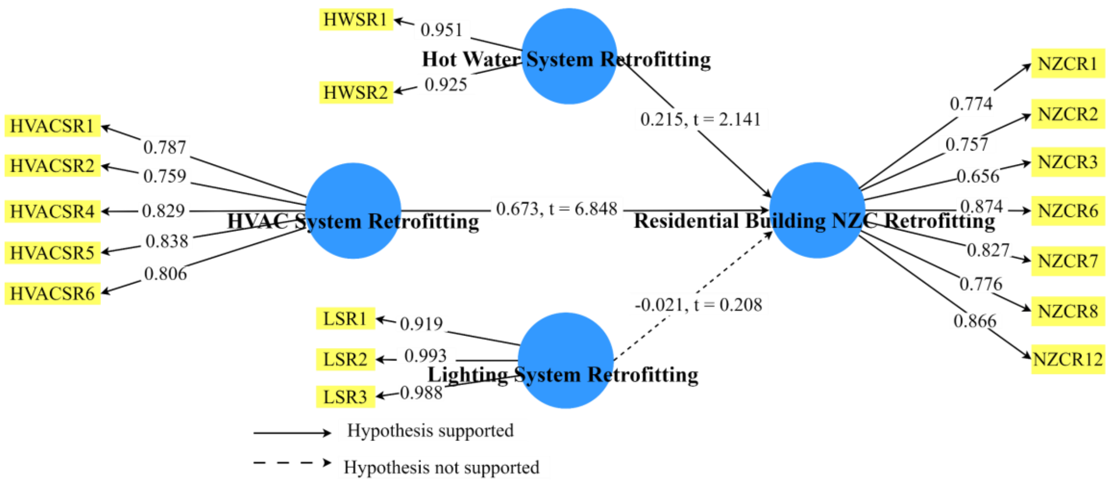


Figure 6.4: Structural model for energy system upgrades.

Table 6.14: Hypotheses for energy system upgrades.

Hypothesis number	Hypotheses	Path coefficient	t-value	p-value	Decision
H2a	HVAC system retrofitting -> Residential building NZC retrofitting	0.673	6.848	0.000	Hypothesis supported
H2b	Hot water system retrofitting -> Residential building NZC retrofitting	0.215	2.141	0.032	Hypothesis supported
H2c	Lighting system retrofitting -> Residential building NZC retrofitting	-0.021	0.208	0.835	Hypothesis not supported

6.6.3 Renewable Energy Upgrades

6.6.3.1 Evaluation of Measurement Model

The measurement items NZCR3, NZCR4, NZCR5, NZCR8, NZCR9, NZCR10, and NZCR11 were eliminated due to their factor loading values below 0.5 to conserve the reliability and validity of the measurement model. Tables 6.15-18 present the findings of the reliability and validity assessments conducted on the assessment of the measurement model. The explanations for the evaluation of reliability and validity constructed on evaluation results of the measurement model (Table 6.15), Fornell and Larcker criterion (Table 6.16), HTMT ratios

(Table 6.17), and cross-loadings (Table 6.18) remain consistent with the explanations presented in section 4.5.1.

Table 6.15: Evaluation of measurement model for renewable energy upgrades.

Construct	Measurement item	Factor loading	Cronbach's alpha	Composite reliability	AVE
Solar energy	SE1	0.890	0.741	0.885	0.794
	SE2	0.892	-	-	-
Wind energy	WE1	0.951	0.865	0.936	0.880
	WE2	0.924	-	-	-
Residential building NZC retrofitting	NZCR1	0.801	0.894	0.922	0.702
	NZCR2	0.781	-	-	-
	NZCR6	0.864	-	-	-
	NZCR7	0.877	-	-	-
	NZCR12	0.862	-	-	-

Table 6.16: Results of Fornell and Larcker criterion for renewable energy upgrades.

	Solar energy	Wind energy	Residential building NZC retrofitting
Solar energy	**0.891**		
Wind energy	0.599	**0.938**	
Residential building NZC retrofitting	0.681	0.592	**0.838**

Table 6.17: HTMT ratio values for renewable energy upgrades.

	Solar energy	Wind energy	Residential building NZC retrofitting
Solar energy			
Wind energy	0.744		
Residential building NZC retrofitting	0.827	0.657	

Table 6.18: Cross-loading values for renewable energy upgrades.

	Solar energy	Wind energy	Residential building NZC retrofitting
SE1	**0.890**	0.512	0.604
SE2	**0.892**	0.556	0.609
WE1	0.597	**0.951**	0.609
WE2	0.521	**0.924**	0.490
NZCR1	0.514	0.467	**0.801**
NZCR2	0.522	0.403	**0.781**
NZCR6	0.511	0.437	**0.864**
NZCR7	0.672	0.572	**0.877**
NZCR12	0.603	0.568	**0.862**

6.6.3.2 Analysis of Structural Model

Figure 6.5 represents the final structural model of renewable energy upgrades, incorporating the path coefficients and t-values. It is noteworthy that retrofitting measures utilizing solar energy are highly appropriate for residential building NZC retrofitting, as indicated by a high path coefficient of 0.508. Furthermore, hypotheses H3a and H3b, formulated to investigate the influence of solar energy and wind energy retrofitting measures on the NZC retrofitting of residential buildings, were supported at a significant level of 0.01 and 0.05, respectively. This support was evidenced by their respective t-values (Table 6.19), which exceed the thresholds of 2.58 and 1.96.

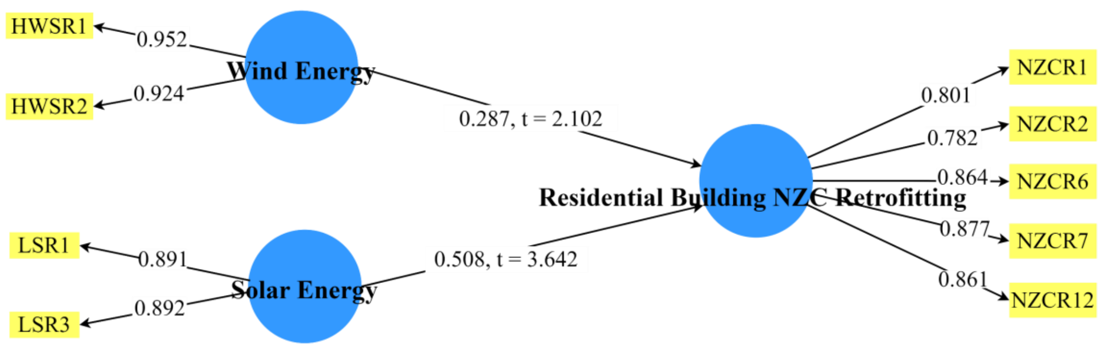


Figure 6.5: Structural model for renewable energy upgrades.

Table 6.19: Evaluation of the structural model for renewable energy upgrades.

Hypothesis Number	Hypotheses	Path Coefficient	t-Value	p-Value	Decision
H3a	Solar energy -> Residential building NZC retrofitting	0.508	3.642	0.000	Hypothesis supported
H3b	Wind energy -> Residential building NZC retrofitting	0.287	2.102	0.036	Hypothesis supported

6.6.4 Discussion of Results

6.6.4.1 Building Envelope Upgrades

The analysis conducted utilizing PLS-SEM on the gathered data provided support for identifying the most suitable measures concerning building envelope enhancements within the context of achieving NZC in residential buildings in Hong Kong. Findings from the analysis indicated that wall and window retrofitting measures are most suitable for Hong Kong residential buildings with notably higher t-values, while roof, floor, and door retrofitting measures are difficult to implement, as evidenced by lower t-values. As evidenced by He et al. (2020), wall and window retrofitting measures have the potential to significantly reduce energy consumption while simultaneously enhancing the indoor environmental quality for building occupants. He et al. (2021b) further mentioned that wall and window retrofitting are the major retrofits associated with building envelope to achieve zero emissions. In addition, the complexity of the high-rise residential structures may make retrofitting the floor, roof, and door components difficult (Cianfrone et al., 2016). Consequently, focusing on wall and window retrofitting methods may be more important than committing resources to roof, floor, and door retrofitting efforts for meeting NZC in Hong Kong residential buildings.

Studies conducted by Heidari et al. (2022) and Shadram et al. (2020) further corroborated the efficacy of wall and window retrofitting measures compared to other building envelope enhancements in achieving carbon neutrality in existing residential buildings through empirical investigations in Canada and Sweden, both developed regions. Despite the established importance of wall and window retrofitting measures, the HKGBC's retrofitting guidebook recommends measures that include wall, window, door, and roof retrofitting (HKGBC, 2023). Nonetheless, this guidebook is intended to serve as a comprehensive resource for a variety of building types, including residential, commercial, and industrial structures. As a result, the findings of this study could provide useful insights into identifying acceptable measures designed specifically for residential buildings in Hong Kong, and it would be supportive in developing such a guidebook unique to residential building retrofitting.

The results indicated that the implementation of wall insulations, shadings, and green facades as the most supportive measures within the category of wall retrofitting, whereas the installation of triple-glazed windows and double-glazed windows with polyvinylchloride window frames stood as the most supportive retrofitting measures within the category of window retrofitting. A study conducted by Boeri et al. (2016) showed the significant influence of facade insulation and window retrofitting with shading solutions in supporting carbon neutrality within residential building retrofitting in Italy, which is considered a developed country. Their research found that facade insulation might save up to 50% on expenses, while window shading solutions could save 40% - 50% when compared to traditional approaches used in Italian residential buildings. Furthermore, Madushika et al. (2022) demonstrated the benefits of green facades even in developing countries, demonstrating a considerable 64% reduction in operational expenses and a corresponding decrease in operational carbon emissions in a case study focusing on Sri Lanka. In addition, Almeida and Ferreira (2017) demonstrated the significant impact of wall insulation in achieving carbon neutrality through a comparison of diverse cases from developed countries.

The research conducted by Panagiotidou et al. (2021) further underscored the importance of residential building retrofitting strategies, specifically highlighting the efficacy of wall insulation and the incorporation of triple-glazed windows in the pursuit of zero-carbon residential structures, as evidenced by a case study conducted in Greece. Their analysis emphasized that choosing wall insulation and triple-glazed windows represents a cost-effective method for achieving zero-carbon residential structures in Greece. Similarly, Lingard (2021) corroborated these findings by emphasizing that wall retrofitting with insulation and window retrofitting utilizing lower u-value glasses emerge as cost-effective solutions in attaining carbon neutrality, based on a case study focused on retrofitting residential buildings within the United Kingdom.

Accordingly, the implementation of wall and window retrofitting measures is expected to play a critical role in reducing the operational carbon emissions from existing residential buildings in achieving the NZC within Hong Kong. Therefore, in the pursuit of attaining NZC standards within residential buildings in developed regions, a strategic emphasis on wall and window retrofitting is advisable. This approach aims to mitigate the complexities inherent in high-rise buildings, thereby facilitating an effective transition toward NZC compliance. In light of that, these findings hold significant implications for practitioners and policymakers involved in devising strategies to attain NZC standards within existing residential building stocks in developed economies

6.6.4.2 Energy system upgrades

The findings revealed that retrofitting measures pertaining to the HVAC system and hot water system exerted a high appropriateness for residential building NZC retrofitting in Hong Kong. However, the analysis demonstrated that retrofitting of lighting systems does not highly contribute to residential building NZC retrofitting within Hong Kong. The majority of the building occupants in Hong Kong are already using energy-efficient light bulbs such as LED, since it is an easier way for them to minimize their electricity bill (Chung, 2012). It indicates that the carbon reduction from the lighting system has already been reduced within the residential buildings in Hong Kong.

Further analysis highlighted specific retrofitting measures under the HVAC system category were deemed highly suitable for Hong Kong residential buildings. These measures included the upgrade of the HVAC system, implementation of efficient heating and cooling set points, utilization of efficient heat pumps, boilers, and cooling sources, as well as the application of a new central heating system. The adoption of air-source heat pumps (ASHP) in residential buildings can result in a 47% reduction in emissions (Heidari et al., 2022), thus proving to be an effective measure for achieving the zero-emission target in existing residential buildings. Additionally, the use of boilers that are certified as “ENERGY STAR” signifies the reduction of operational carbon emissions from the utilization of energy-efficient boilers in residential buildings (Charles et al., 2019). Further, respondents have underscored the importance of utilizing air conditioning units that incorporate environmentally friendly refrigerant materials such as R32, given that most residential units are using old window air conditioners which constitute a significant energy consumption source within residential buildings in Hong Kong. Hence, respondents advocated for the replacement of outdated air conditioning units with newer models as a proactive measure to diminish their contribution to global warming and address broader climate change concerns.

Regarding hot water systems, the analysis results indicated that the use of electrical water heaters and the installation of domestic hot water (DHW) systems hold significance. In comparison to conventional natural gas-based water heaters, which emit more carbon during the burning of fossil fuels, electric water heaters exhibit higher efficiency and cleaner operation (Heidari et al., 2022). However, analysis revealed that its impact on attaining the NZC target was comparatively lower compared to HVAC system upgrades. In addition, respondents have conveyed in the questionnaire that a methodical and prioritized approach towards upgrading or replacing high energy-consuming systems, coupled with enhanced levels of control, presents a more effective strategy for attaining NZC within the existing residential buildings in Hong Kong.

6.6.4.3 Renewable energy upgrades

Renewable energy upgrades have been identified as playing a paramount role in the attainment of NZC in residential buildings. The study specifically highlights the integration of solar and wind energy as crucial measures for achieving NZC residential buildings. Solar energy can be effectively harnessed through the utilization of PV panels installed on the roof and walls, as well as through its application as a thermal collector for DHW production. On the other hand, wind energy can be harnessed through the installation of wind turbines or the installation of wind-assisted ventilation systems. The adoption of renewable energy sources is imperative in NZC retrofitting measures as they emit significantly lower levels of carbon emissions (Morris, 2023). This is particularly important in offsetting the carbon releases resulting from operational energy usage and the embedded carbon in retrofitting materials used in building envelope upgrades and energy system upgrades. However, findings revealed that solar energy exerts a greater influence on achieving NZC targets compared to wind energy. This preference for solar energy may be attributed to its widespread usage as a renewable energy source in urban environments (Panagiotidou et al., 2021).

The data analysis performed in the current study provides evidence indicating that the installation of PV panels, rather than thermal collectors, holds more support in the pursuit of NZC targets. Thermal collectors primarily generate heat, whereas PV panels are employed for electricity generation, which contributes to higher carbon emissions from existing residential buildings in developed regions (Hamburg et al., 2020). However, it should be noted that space limitations and shading issues caused by neighboring structures in developed regions, particularly in high-rise buildings, often pose challenges for PV panel installation.

Nonetheless, preliminary research conducted by Panagiotidou et al. (2021) suggested that rooftop areas and facades of residential buildings are suitable for PV panel installation. Liu et al. (2022) further explained that PV panels solely installed on the roof of low-rise residential buildings can provide sufficient electric energy for two comparable low-rise buildings. However, achieving NZC targets in medium and high-rise residential buildings may require positioning of PV panels on both roofs and facades. In a study by Abdelhafez et al. (2021), it was advised to install 30^0 tilt PV panels on the rooftop to maximize energy production in a residential building scenario in Saudi Arabia. Based on these findings, it is recommended to consider the installation of PV panels on the rooftops of residential buildings in Hong Kong and other similar developed regions to effectively progress towards NZC residential buildings.

Accordingly, as illustrated in the hypothetical model presented in Figure 6.2, the integration of these three categories of measures collectively paves the way toward achieving NZC in retrofitting residential buildings. As validated through the PLS-SEM, the implementation of building envelope upgrades and energy system upgrades assists in alleviating operational carbon releases by reducing the energy demand within residential buildings, thereby decreasing initial investments in renewable energy upgrades, which is an essential source in achieving NZC. Subsequently, "renewable energy sources" such as solar energy and wind energy are employed to offset the remaining carbon emissions and embodied carbon arising from retrofitting materials, thereby facilitating the NZC residential buildings. Figure 6.6 visually outlines the implementation pathway for retrofitting measures designed to achieve Net Zero Carbon (NZC) in existing residential buildings within high-density urban areas.

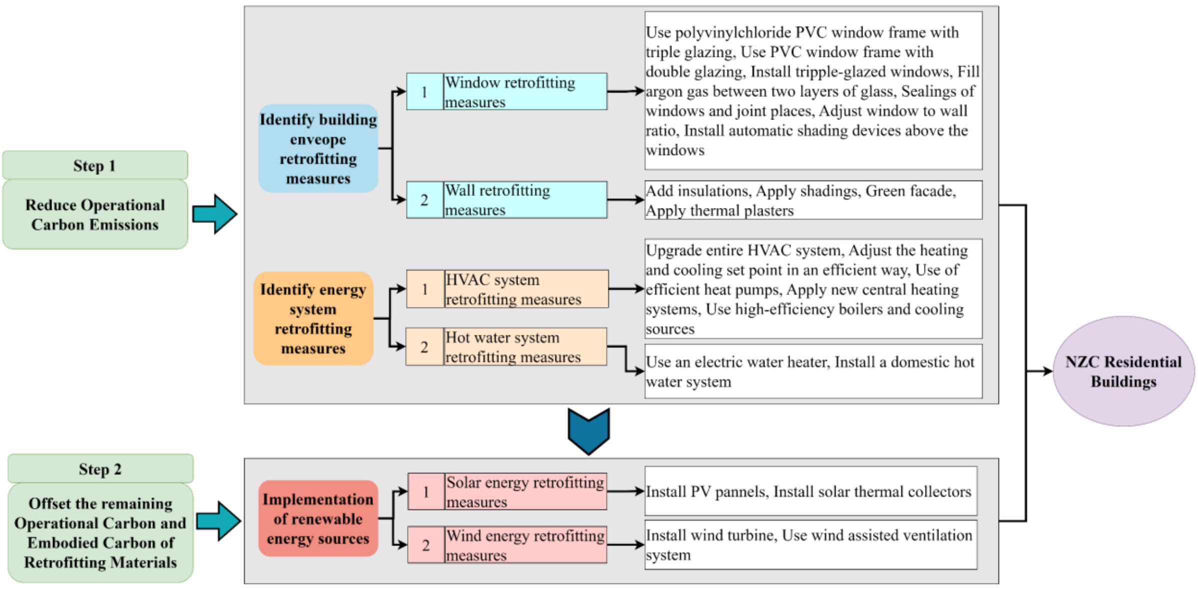


Figure 6.6: Implementation pathway of measures for NZC retrofits of residential buildings.

This implementation pathway was proposed for residential building NZC retrofitting based on the findings from Hong Kong. Even though it is based on Hong Kong, it might be useful for other similar developed regions to achieve NZC residential buildings. When retrofitting residential buildings to NZC, it is necessary to identify the most suitable retrofit measures that can give optimal results. Accordingly, the first step was to identify the measures related to the building envelope and energy system retrofits to reduce the operational carbon emissions from the existing residential buildings. Identification of renewable energy sources to offset the remaining operational carbon emissions and embodied carbon of retrofit materials was the second step in the implementation pathway of measures. Accordingly, this would be useful for researchers as well as decision-makers in selecting measures to decide the optimal set of retrofit measures to achieve NZC residential buildings. Further, practitioners and policymakers can use this during their efforts to promote the residential building NZC retrofitting to achieve a zero-emission built environment.

6.7 Chapter Summary, Contributions, and Limitations

Residential building retrofitting to achieve NZC has been recognized as a crucial step towards solving the issues caused by climate change. To attain NZC residential buildings, a variety of retrofitting measures are available in the market, targeting the building envelopes, energy systems, and implementation of renewable energy technologies. However, a knowledge gap persists regarding the selection of retrofitting measures for achieving NZC status in existing residential buildings. To bridge this knowledge gap, empirical data were gathered by two questionnaire surveys. First, building occupants' preferences were assessed using the 123 responses received for the questionnaire survey with building occupants. Then, a mean score ranking and PLS-SEM analysis were conducted using the 52 responses received for the questionnaire from construction experts.

The findings revealed that occupants exhibited a predominant inclination towards retrofitting existing residential buildings using renewable energy sources, as opposed to other energy-efficient measures pertaining to building envelopes and energy systems retrofitting. Notably, among the renewable energy options, solar energy garnered the highest preference from occupants. In terms of energy systems, lighting systems emerged as the most preferred retrofitting measure, while wall retrofitting stood as the preferred measure within the building envelope category.

Further, findings from PLS-SEM analysis indicated that retrofitting measures targeting the building envelope, specifically wall and window retrofitting, could be among the most suitable approaches for advancing toward NZC status in residential buildings in Hong Kong. Similarly, measures related to HVAC and hot water systems appear to have considerable prospects for improving the energy systems of such buildings in Hong Kong. Furthermore, results indicated that the integration of solar energy sources played a significant role in the attainment of NZC residential buildings from existing buildings in the context of Hong Kong. These findings can serve as a motivational tool for academics, industry practitioners, and policymakers, encouraging them to prioritize NZC retrofitting as a means of establishing a sustainable built environment.

Moving forward, it is recommended to expand upon the present chapter by identifying and analyzing diverse measurement items related to the identified retrofitting measures. In addition, future studies are recommended to focus on a quantitative analysis of professional stakeholder's perspectives on NZC retrofitting measures. Furthermore, future studies recommended incorporating the findings of this study when performing comparison analysis covering both building occupant's and professional stakeholder's perspectives on residential building NZC retrofitting measures. Such an approach would yield valuable insights for the effective implementation of NZC retrofitting in existing residential buildings.

Academics can leverage the quantitative evidence provided by this chapter to advocate for the implementation of retrofitting measures aimed at achieving NZC in existing buildings. In addition, further studies can be conducted in the future to supplement the current research findings through qualitative or quantitative analysis. Industry practitioners can gain a clearer understanding of the significance of building envelope upgrades, energy system upgrades, and the integration of renewable energy sources, thereby facilitating the successful attainment of NZC within the construction industry. Furthermore, the findings may offer guidance to practitioners and companies involved in the field of retrofitting, aiding them in developing innovative measures that are tailored to occupant preferences. In addition, retrofit strategies can be developed by integrating measures preferred by occupants, aiming to maximize the impacts of NZC retrofitting in high-density urban settings. Policymakers can utilize these quantitative findings to develop strategies that promote NZC within the construction sector. Consequently, this study relates to the decision-making process regarding the numerous retrofitting measures that influence the achievement of NZC in existing building stock.

Despite its contributions, this chapter has certain limitations. First, this chapter was limited to residential buildings in Hong Kong, and two questionnaire surveys were limited to building occupants and experts. Although the number of responses was found suitable for doing PLS-SEM analysis; still, it remains relatively small. Nonetheless, the findings of this chapter offer valuable insights into the suitability of different retrofitting measures concerning building envelope, energy systems, and renewable energy upgrades in the pursuit of NZC for existing residential buildings. Additionally, the findings primarily reflect the environment of Hong Kong, thus reducing the generalizability of the results, which is a common constraint in nation-specific studies. Nevertheless, the implications and findings of this chapter could be valuable to academics, practitioners, policymakers, and advocates in other developed regions worldwide.

CHAPTER SEVEN

7.0 Energy Simulation and Development of Retrofit Strategies

7.1 Introduction

Chapter 6 analyzes the retrofitting measures that can be used in Hong Kong residential buildings to achieve NZC based on the perspectives of building occupants and experts in the domain of NZC retrofitting. The current chapter analyzes the performance of retrofit measures and develops retrofit strategies that can be used to achieve NZC residential buildings in Hong Kong. This chapter is developed based on the case study and model simulation findings. The details of the case study were described in section 3.7.1, while section 3.7.2 described the IESVE, which is used as the simulation tool. The primary objective of this chapter is to formulate retrofit strategies aimed at attaining NZC status for the existing residential buildings in Hong Kong. To achieve this, the findings in sections 6.2 and 6.6 were used to decide retrofit measures. In addition, the selected case was modeled using IESVE and simulated by implementing the selected retrofit measures.

The model simulation was used to decide the parameters of the retrofit measures with the aim of developing retrofit strategies. In addition, the current chapter used simulation to evaluate the energy consumption, carbon emissions, and occupant dissatisfaction with numerous retrofitting measures associated with the building envelopes, energy systems, and renewable energy upgrades on attaining NZC status in residential buildings, particularly within Hong Kong. Hence, this chapter provides information necessary for developing retrofit strategies, and the results of this chapter would guide decision-makers in making optimal decisions on residential building NZC retrofitting.

7.2 Identification of Individual Retrofit Measures

Chapter 6 analyzed the different retrofit measures: building envelope upgrades, energy system upgrades, and renewable energy upgrades based on the opinions of the building occupants and experts in the domain of NZC retrofitting. The findings from Chapter 6 were used in this chapter to identify individual retrofit measures that can be used in deciding the retrofit strategies to achieve NZC residential buildings in Hong Kong. As a result, Table 7.1 represents the hierarchical classification of various retrofit categories, contrasting the perspectives of experts and building occupants.

Table 7.1: Ranking of retrofit measures based on the perspectives of experts and building occupants.

Retrofitting category	Rank	Measure type	Rank	Measure type	Rank
Building Occupants				*Experts*	
Renewable energy	1	Solar energy	1	Solar energy	1
		Wind energy	2	Wind energy	2
Energy system	2	Lighting system retrofitting	1	HVAC system retrofitting	1
		HVAC system retrofitting	2	Hot water system retrofitting	2
		Hot water system retrofitting	3		
Building envelope	3	Wall retrofitting	1	Window retrofitting	1
		Window retrofitting	2	Wall retrofitting	2
		Roof retrofitting	3		
		Door retrofitting	4		
		Floor retrofitting	5		

After comparing the results of two separate surveys, the study decided to use solar energy as a renewable energy source to develop retrofit strategies to upgrade residential buildings to NZC. Despite the occupant's preference for retrofitting lighting systems, as revealed by survey responses, the results of section 6.6.2 did not reveal its suitability in residential building NZC retrofitting. As a result, the study chose HVAC system retrofitting as it is the top-ranked measure in energy system upgrades based on the results in Table 7.1. Furthermore, window and wall retrofitting measures were chosen from building envelope upgrades since they had high ranks among experts and building occupants. Further, being the building envelope is the main retrofitting component associated with buildings (He et al., 2021b), both wall and window retrofitting measures were considered in this study.

After deciding the retrofit types by comparing the results of two questionnaire surveys, the retrofit measures were selected with the use of the results in section 6.6. Accordingly, Table 7.2 illustrates the retrofit measures selected for future activities in this study.

Table 7.2: Retrofit measures used to develop retrofit strategies.

Retrofitting category	Measure type	Measure
Building envelope upgrades	Wall retrofitting	Wall insulation and shading
	Window retrofitting	Use PVC-framed triple-glazed windows and PVC-framed double-glazed windows
Energy system upgrades	HVAC system retrofitting	Replace air conditioning units
Renewable energy upgrades	Solar energy	Install PV panels

In order to define the retrofit strategies, the measures under selected retrofit categories were applied within the chosen case study to assess their energy consumption, carbon emissions, and PPD.

7.3 Case Study Modeling and Validation of the Model

The details of the selected case study are described in section 3.7.1. As the initial step for the simulation, the selected two-person residential unit was modeled in the virtual environment using IESVE (Figure 7.1).

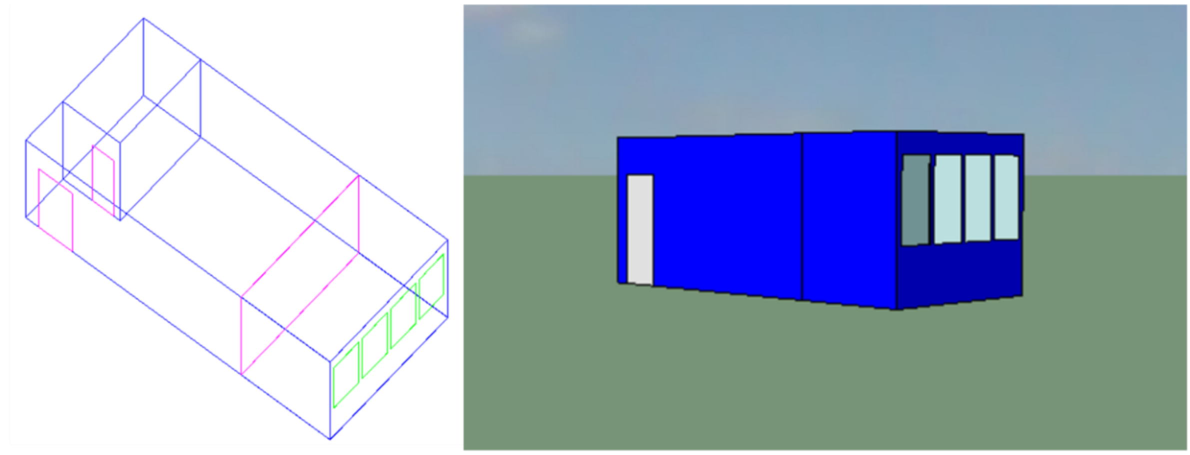


Figure 7.1: Selected residential unit as in IESVE.

The model was characterized with respect to its geographical location, occupants, thermal attributes, construction specifics, and other requisite details essential for the software to accurately simulate the chosen scenario. Weather data pertinent to Hong Kong was acquired in the form of an EnergyPlus Weather file and integrated into the IESVE Aplocate platform to update the building's location and climatic parameters. Moreover, the Apache interface within IESVE was utilized to enhance the construction and thermal details of the residential unit. Notably, the unit features brick and partition walls with U-values of 2.32 W/m^2K and 1.66 W/m^2K, respectively, along with glass windows framed with aluminum. Furthermore, the model was refined by incorporating specifics of the air conditioning unit (with a cooling capacity of 7000BTU/h), water heater (temperature from 35^0C-75^0C), and lighting fixtures. To configure occupancy and cooling settings, it was stipulated that only one individual occupied the premises on weekdays from 7.00 am to 6.00 pm, while both residents were present during the remaining time and on weekends.

Following the characterization of the model as per the selected residential unit, a calibration process was initiated. Calibration involves the comparison of simulated data with actual data, adjusting model inputs to enhance the accuracy (Ascione et al., 2020). In this context, the Mean Bias Error (MBE) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE) were employed to assess the accuracy of simulated data against metered data. As per ASHRAE (2014) the MBE evaluates the fidelity of numerical forecasts relative to measurements but may not rectify cancellation errors arising from opposing data values. Conversely, CV(RMSVE) elucidates uncertainties in model predictions and rectifies potential discrepancies stemming from the incorporation of positive and negative values, thereby averting misconceptions in calibration based solely on MBE (ASHRAE, 2014). To validate the proper model calibration, MBE should fall within ± 5%, and CV(RMSE) should not exceed 15%. These error metrics were computed using equations 7 and 8 specified by ASHRAE (2014).

$$MBE = \frac{\sum_{i=1}^{N_i}(M_i - S_i)}{\sum_{i=1}^{N_i} M_i} \tag{7}$$

$$CV(RMSE) = \frac{\sqrt{\sum_{i=1}^{N_i}[\frac{(M_i - S_i)^2}{N_i}]}}{\frac{1}{N_i}\sum_{i=1}^{N_i} M_i} \tag{8}$$

Where,
M_i = Measured data
S_i = Simulated data
N_i = Number of values used

Given the common practices of utilizing monthly energy consumption data extracted from building energy bills for model calibration purposes (Ascione et al., 2020), the energy bills corresponding to the selected unit spanning from January to December were employed in this research for model calibration. Based on actual monitored conditions, it is evident that energy consumption increases notably from May to September, a period characterized by the peak of summer in Hong Kong. Moreover, in December, the temperature goes to its lowest point due to winter, resulting in heightened energy usage to maintain occupant comfort. Since peak summer in Hong Kong occurs during August and the transition to cooler winter during November signifies a large energy consumption difference between August and November (Hong Kong Observatory, 2025). Figure 7.2 visually represents the comparison between metered and simulated data, offering a graphical insight into these energy consumption patterns across the year.

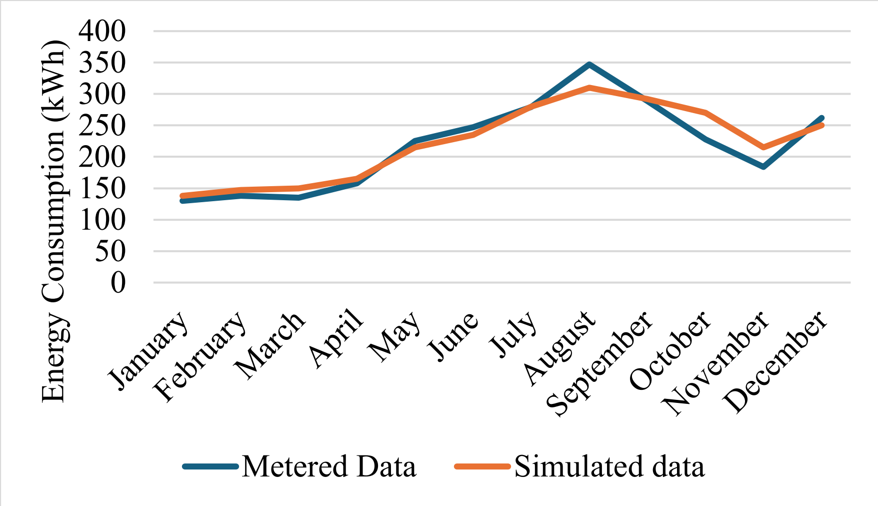


Figure 7.2: Illustration of metered data vs simulated data (January – December, 2024).

The calculated error values for MBE and CV(RMSE) represented -1.72% and 13.98%. Those errors may have arisen due to changes in the building occupants' behaviors and mismatches with building materials. However, the error indicators performed within their predefined thresholds. Therefore, the model underwent effective calibration, acknowledging the contribution of IESVE software. Accordingly, the model is now ready to assess the sustainable performance of individual retrofit measures to develop retrofit strategies.

7.4 Results and discussion on performance evaluation of individual retrofit measures

7.4.1 Retrofit to Building Envelope

Since the model was calibrated, the impact of individual retrofit measures was assessed through the IESVE. Accordingly, the annual energy consumption, carbon emissions, and the PPD associated with wall retrofitting (insulation and shading) and window retrofitting (double and triple-glazed windows with PVC frames) were measured. Given the relatively high U-value of the wall (2.32 W/m^2k), external wall insulation was implemented using Expanded Polystyrene (EPS) in response to this thermal inefficiency (Sharif & Hammad, 2019; Wei et al., 2024). Further, EPS is a popular wall insulation material in China due to its excellent thermal performance (He et al., 2021a). According to Zhu et al. (2011), the insulation thickness of buildings in southern China ranges between 30mm to 60mm, while it ranges between 80mm to

120mm in northern China to align with the prescribed thermal requirements for external walls dictated by residential building energy efficiency design standards across different climate zones. Since Hong Kong is closer to the southern part of China, the study considered 25mm, 50mm, 75mm, and 100mm thicknesses for wall insulation.

Different types of shading treatments have different impacts on the amount of solar heat entering a room. It has been confirmed that external shading systems serve better in reducing solar heat gain than internal devices, as external shading devices can directly reduce solar heat gain through windows (Cho et al., 2014; Ossen et al., 2005). The most common external shading devices are overhangs, which have been examined for energy reduction and indoor comfort in many prior studies (S. Liu et al., 2019; Ossen et al., 2005). Within the chosen building, only two walls were external, with the remainder serving as partition walls. Among the external walls, one faced shading from an adjacent building, while the other was fully exposed to sunlight. Consequently, horizontal wall shadings were applied to the externally exposed wall to mitigate solar heat gain. Four wall shades with 10mm concrete thickness were horizontally positioned at 330mm intervals, with one positioned above the windows and the remaining three located below the windows. S. Liu et al. (2019) have demonstrated that external wall shading lengths from 100mm to 700mm are energy efficient for Hong Kong residential buildings. However, based on the model performances, this study considered horizontal external wall shading lengths of 100mm, 200mm, 300mm, and 400mm.

In relation to the windows, the designated building originally featured single-glazed windows with aluminum frames, exhibiting a thermal transmittance value of 5.224 W/m^{2}k. Double and triple-glazed windows are energy efficient and thermally comfortable compared to single-glazed windows within cooling-dominant areas (Lai & Wang, 2011). Consequently, the windows underwent retrofitting, replacing them with triple-glazed and double-glazed alternatives featuring PVC frames. Previous studies showed carbon reductions with the use of 3mm, 6mm, 9mm, 12mm, and 15mm thick glass for double and triple-glazed windows (Ascione et al., 2020; He et al., 2021a). Based on the model performances, this study selected 4mm and 6mm glasses for double and triple-glazed windows as indicated in Table 7.3.

Based on the information provided, each retrofit measure underwent individual simulation across various parameters to assess annual energy consumption, carbon emissions, and occupant dissatisfaction percentages. The performance of the chosen retrofit measures is depicted in Table 7.3, while Figure 7.3 visually represents the variations in annual energy consumption, annual carbon emissions, and PPD values.

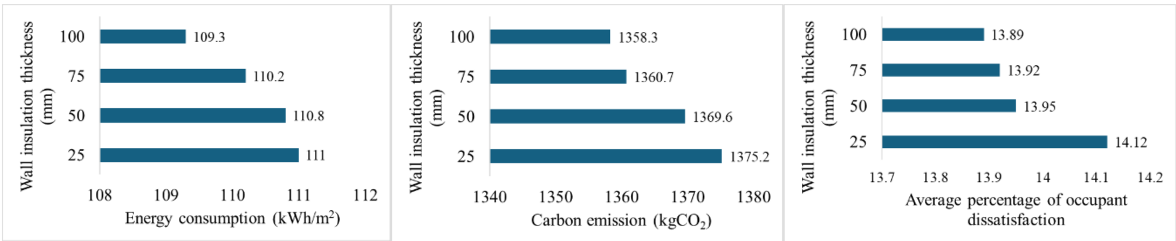


Figure 7.3(a): Wall insulation

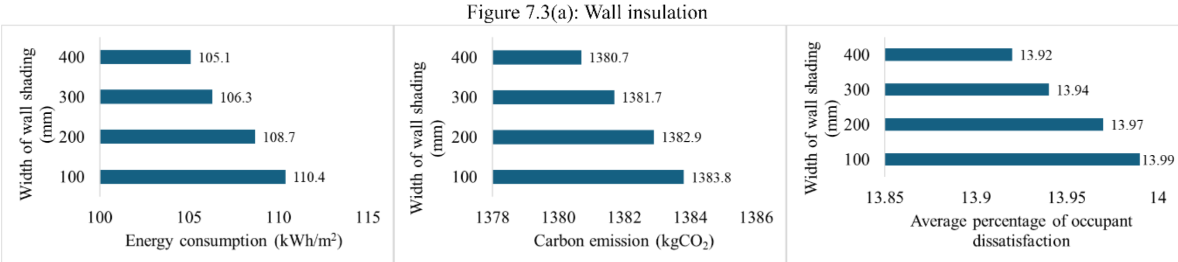


Figure 7.3(b): Wall shading

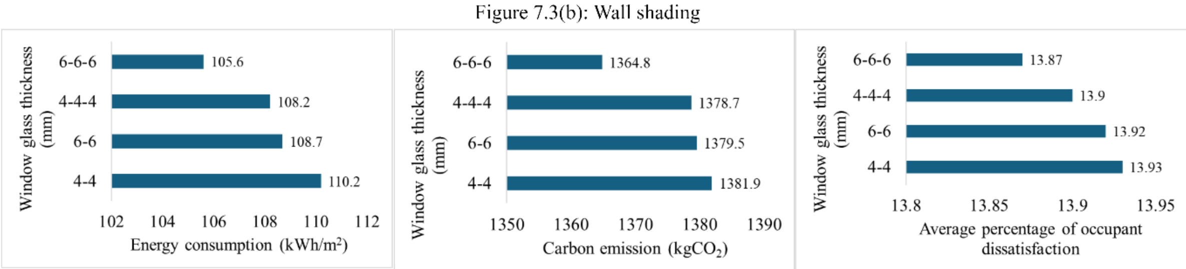


Figure 7.3(c): Window retrofitting with double and triple-glazed windows with PVC frames

Figure 7.3: Annual energy consumption, carbon emissions, and PPD associated with wall and window retrofit measures.

Table 7.3: Details of changes in energy consumption, carbon emissions, and PPD with the wall and window retrofit measures.

Retrofit measure	Annual energy consumption (kWh/m^2)	Annual carbon emissions ($kgCO_2$)	PPD (%)
Base Case	111.4	1,384.5	14.68

Wall insulation			
25 mm thick (0.544 W/m^{2}k)	111.0	1,375.2	14.12
50 mm thick (0.4705 W/m^{2}k)	110.8	1,369.6	13.95
75 mm thick (0.392 W/m^{2}k)	110.2	1,360.7	13.92
100 mm thick (0.306 W/m^{2}k)	109.3	1,358.3	13.89
Wall shading			
100 mm	110.4	1,383.8	13.99
200 mm	108.7	1,382.9	13.97
300 mm	106.3	1,381.7	13.94
400 mm	105.1	1,380.7	13.92
Windows retrofitting			
4-4 mm thick glass with PVC frame (4.302 W/m^{2}k)	110.2	1,381.9	13.93
6-6 mm thick glass with PVC frame (4.239 W/m^{2}k)	108.7	1,379.5	13.92
4-4-4 mm thick glass with PVC frame (3.746 W/m^{2}k)	108.2	1,378.7	13.90
6-6-6 mm thick glass with PVC frame (3.678 W/m^{2}k)	105.6	1,364.8	13.87

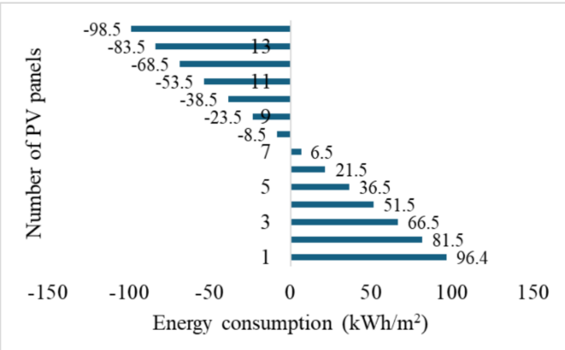
As per the simulation results presented in Table 7.3, the thickness of the insulation layer, the length of the wall shading, and the thickness of the glazing significantly influence energy consumption, carbon emissions, and occupant dissatisfaction. An increase in the parameters of insulation, shading, and glass thickness correlates with a decrease in energy consumption, carbon emissions, and occupant dissatisfaction. Lower U-values in wall insulation and window retrofitting indicate enhanced performance owing to their superior heat transfer rates within the building envelope. Notably, the research findings reveal that a 400mm length wall shading results in the least annual energy consumption, while the lowest annual carbon emissions are associated with 100mm wall insulation. Given Hong Kong's subtropical climate, wall shading practices are commonly employed to enhance energy efficiency in buildings (S. Liu et al., 2019). Furthermore, the adoption of windows with lower U-values contributes to improved occupant comfort due to their effective thermal characteristics (Lee et al., 2023). Consequently, within the context of building envelope retrofit scenarios, the utilization of 6-6-6mm triple-glazed windows with PVC framing is identified as offering the lowest PPD value.

7.4.2 Retrofit to Energy System

The study found that retrofitting the HVAC system was the most suitable energy system enhancement for residential buildings in Hong Kong. Among the different measures available to retrofit the HVAC system, the study selected an upgrade of the entire HVAC system as the most suitable measure to achieve NZC residential buildings based on the findings in section 6.6.2. Concerning the HVAC system of the selected building, the main element was the air conditioner. Given that the selected building employed a Grade 3 window air conditioner with a cooling capacity of 7000 BTU/h, the study considered upgrading it to a Grade 1 window air conditioner with a cooling capacity of 8530 BTU/h. Following the execution of model simulations post-air conditioner modification, the annual energy consumption decreased to 101.5 kWh/m^2, while annual carbon emissions reduced to 1261.20 $kgCO_2$. Despite these enhancements, occupant dissatisfaction remained consistent with the base case, as the alteration in the air conditioners did not influence comfort levels, notwithstanding its positive effects on carbon emissions reduction and energy consumption. The change in the amount of energy used to heat or cool the air conditioner was the main difference between the existing and the new air conditioner. Hence, occupant dissatisfaction did not show any changes with the replacement of the new air conditioner.

7.4.3 Retrofitting using Renewable Energy

The incorporation of PV panels was identified as the primary renewable energy enhancement measure to facilitate the realization of NZC in Hong Kong residential buildings. PV panels can be installed either on the rooftop or at ground level. The rooftop represents an optimal location for PV panel installation due to its exposure to sunlight, enabling efficient conversion of solar energy into electricity (He et al., 2021a). As a result, the present study considered the total floor as the maximum area of the PV installation to determine the optimized area of PV panel installation on the rooftop to achieve NZC from existing residential buildings in Hong Kong. Consequently, monocrystalline solar panels, each with a power output of 322 W and dimensions of 1.6m X 1m, were selected for deployment, with a total capacity of 14 panels feasible for installation. Various numbers of PV panels were evaluated in the study, ranging from the installation of a single panel (minimum area) to the maximum capacity of 14 panels, representing 14 different areas of panel installation. Notably, the integration of PV panels did not yield any discernible alteration in the PPD. However, its impact on annual energy consumption and annual carbon emissions is represented in Table 7.4 and visualized in Figure 7.4.



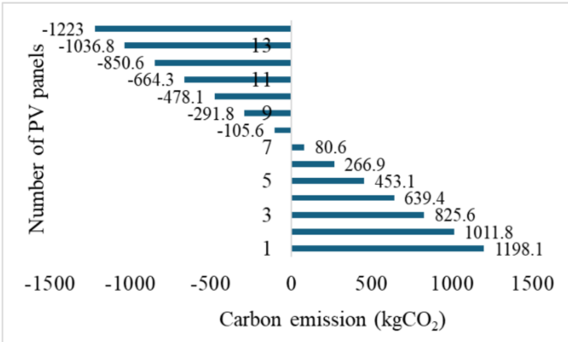


Figure 7.4: Annual energy consumption, carbon emissions, and PPD associated with PV panel installation.

Table 7.4: Details of changes in energy consumption, carbon emissions, and PPD with the PV panel installation.

Retrofit measure	Annual energy consumption (kWh/m^2)	Annual carbon emissions ($kgCO_2$)	PPD (%)
Base Case	111.4	1,384.5	14.68
PV panel installation			
1 panel	96.4	1,198.1	14.68
2 panels	81.5	1,011.8	14.68
3 panels	66.5	825.6	14.68
4 panels	51.5	639.4	14.68
5 panels	36.5	453.1	14.68
6 panels	21.5	266.9	14.68
7 panels	6.5	80.6	14.68
8 panels	-8.5	-105.6	14.68
9 panels	-23.5	-291.8	14.68
10 panels	-38.5	-478.1	14.68
11 panels	-53.5	-664.3	14.68
12 panels	-68.5	-850.6	14.68
13 panels	-83.5	-1,036.8	14.68
14 panels	-98.5	-1,223.0	14.68

As depicted in Table 7.4, an increase in area corresponds to a gradual decrease in both energy consumption and carbon emissions. While solar energy serves as a key source of energy generation, occupant dissatisfaction remains relatively consistent with the base case throughout the evaluation. Notably, upon reaching the area associated with the installation of 8 PV panels, the system began to generate surplus energy for the building, consequently reducing carbon emissions. In this scenario, the base case can attain NZC status by incorporating more than 8 PV panels, enabling the offsetting of embodied carbon from the PV panel installation through the surplus energy generated by the PV panel system. In addition, all these findings highlighted that operational energy serves as the primary contributor to carbon emissions originating from current residential buildings, with carbon emissions reductions achieved through declines in energy consumption. Thus, solar energy emerged as the primary energy source facilitating the realization of NZC in existing residential buildings due to its ability to generate energy without/ less carbon emissions.

7.5 Development of Retrofit Strategies

Based on an analysis of energy consumption, carbon emissions, and occupant dissatisfaction associated with the individual retrofit measures, these measures were utilized to formulate comprehensive retrofit strategies necessary for the optimization process, which is going to be discussed in Chapter 9. Consequently, the proposed retrofit measures including wall insulation, wall shading, the installation of double and triple-glazed windows with PVC frames, and the replacement of the air conditioning unit, were assessed both individually and in combination, as illustrated in Figure 7.5, resulting in the identification of 249 possible retrofit options (Appendix C). Furthermore, for each retrofit option, 15 different scenarios were considered concerning the installation of PV panels, including cases without PV panels and variations in PV coverage ranging from a single panel to a maximum of 14 panels, as specified in section

7.4.3. Ultimately, the simulation results experienced in the above sections led to the development of 3,735 distinct retrofit strategies.

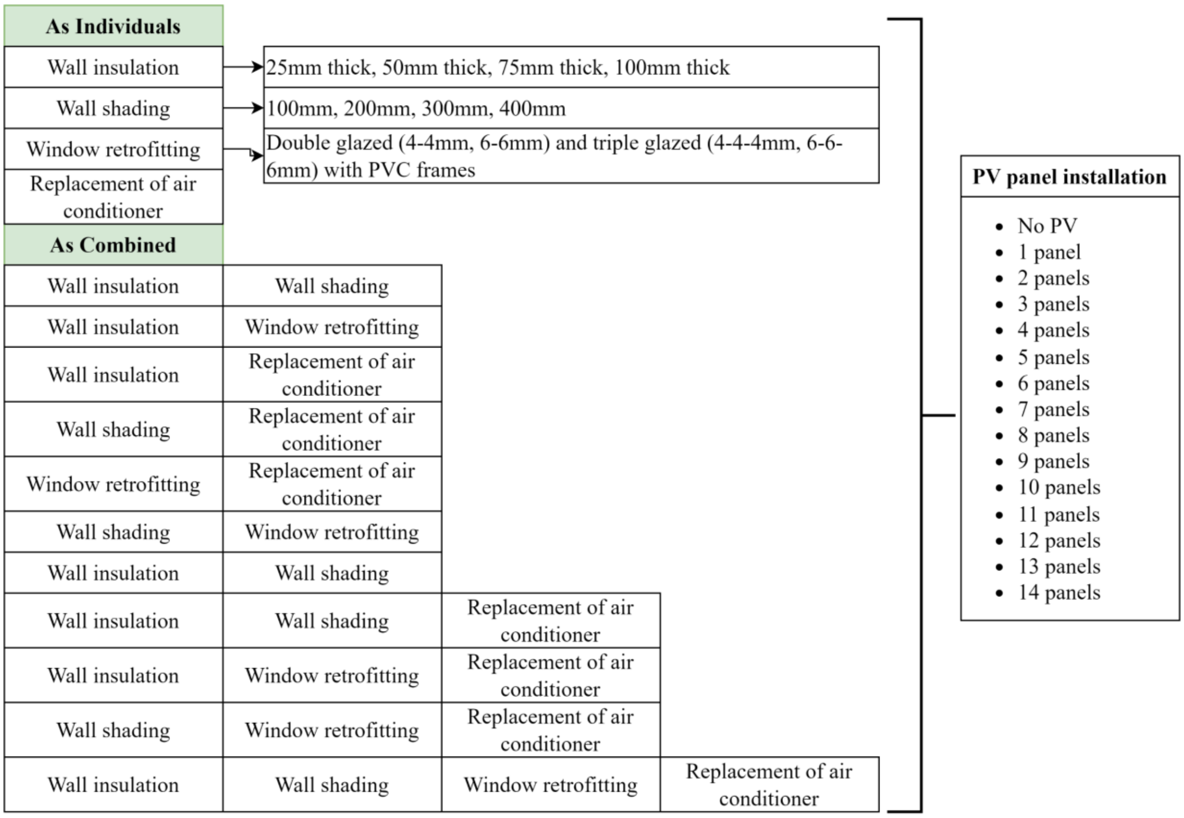


Figure 7.5: Process followed in developing retrofit strategies.

7.6 Chapter Summary, Contributions, and Limitations

Retrofitting existing residential buildings represents the most viable approach to achieving NZC, given their significant contribution to carbon emissions. Since implementing a single retrofit measure is insufficient to achieve NZC in residential buildings, it is necessary to develop comprehensive retrofit strategies that integrate two or more retrofit measures. Therefore, this chapter examined various parameters of retrofit measures identified in Chapter 6 and conducted model simulations to assess their impact on energy consumption, carbon emissions, and occupant dissatisfaction.

Prior to simulating the selected retrofit measures, the chosen case study (two-person residential unit) was modeled using IESVE software and calibrated to ensure its validity. The model's accuracy was confirmed by evaluating MBE and CV(RMSE), both of which fell within the acceptable thresholds. Consequently, the validated model was employed for further simulations incorporating various retrofit measures. Ultimately, 3,735 retrofit strategies were generated, as illustrated in Figure 7.5, incorporating parameters such as wall insulation, wall shading, the installation of double and triple-glazed windows with PVC frames, air conditioner replacement, and PV panel installation. These strategies will form the basis of the optimization process discussed in Chapter 9, which aims to identify optimal retrofit strategies by considering social, environmental, and economic sustainability in the pursuit of NZC residential buildings.

This chapter evaluates energy consumption, carbon emissions, and occupant dissatisfaction associated with retrofit measures, categorized into wall retrofitting, window retrofitting, HVAC system retrofitting, and solar energy-based retrofitting. The findings presented herein will be valuable for researchers specializing in NZC retrofitting strategies for residential buildings, particularly in subtropical regions. Additionally, practitioners can utilize these insights to assess both the individual and combined performance of various retrofit measures when determining appropriate solutions for NZC residential retrofitting.

Despite the development of 3,735 retrofit strategies, this chapter is limited to evaluating the performance of selected measures, specifically wall insulation, wall shading, window upgrades, air conditioner replacement, and PV panel installation. Future research could expand upon these findings by investigating additional retrofit measures within different categories to formulate more comprehensive strategies. Furthermore, as the results are based on the environmental conditions of Hong Kong, their generalizability may be constrained by an inherent limitation of nation-specific studies. Additionally, the simulations were conducted on an annual basis without considering the lifecycle performance of buildings. Future researchers can build upon these findings by incorporating lifetime simulations to better assess long-term energy consumption, carbon emissions, and occupant dissatisfaction. Despite these limitations, the findings of this chapter provide valuable insights for academics, industry practitioners, and policymakers in advancing the development of a zero-carbon built environment through residential building retrofitting.

CHAPTER EIGHT

8.0 Sustainability Analysis of Retrofit Strategies

8.1 Introduction

Chapter 7 developed 3735 retrofit strategies using different parameters of individual retrofit measures considered under building envelope upgrades, energy system upgrades, and renewable energy upgrades, which were selected by assessing energy consumption, carbon emissions, and occupant dissatisfaction using IESVE software. The current chapter analyzes social, environmental, and economic sustainability with the implementation of developed retrofit strategies. Accordingly, this chapter is developed based on the findings from the case study model simulation, embodied carbon calculations, and market survey conducted to collect data on the cost of retrofit materials. Section 3.7 described the tools and methods used to conduct sustainability analysis after retrofitting the building using the developed retrofit strategies in the virtual environment. This chapter attempts to analyze social sustainability, environmental sustainability, and economic sustainability after retrofitting the case study by assessing occupant dissatisfaction, carbon saving, and economic profitability, respectively.

IESVE software was used to conduct model simulation with the developed retrofit strategies, while OneClick LCA software was used to calculate the embodied carbon associated with the retrofit materials. In addition, the details of the market survey were used to calculate the initial cost of retrofit strategies. Finally, all the details were incorporated into Equations from 1 – 6 to analyze the social, environmental, and economic sustainability aspects, considering PPD, carbon savings, and economic profitability, respectively. Accordingly, the findings from this chapter provide valuable guidance for academics as well as decision-makers in making sustainable decisions on residential building NZC retrofitting.

8.2 Results and Discussion of Sustainability Analysis

8.2.1 Social Sustainability

Occupant satisfaction was chosen as the metric for evaluating the social sustainability implications of the retrofitting initiatives. To assess social sustainability post-retrofitting, PPD values, obtainable directly from the VistaPro Comfort analysis tool within the IESVE software during model simulations, were leveraged. Following the validation of the case study model through calibration in section 7.3, the model underwent multiple simulations to implement the devised retrofit strategies (section 7.5). The initial PPD value of the base case stood at 14.68%, indicating that the existing building's dissatisfaction level was below the critical threshold of 20%, as outlined by ASHRAE (2023). Nevertheless, the primary objective of the retrofitting project was to diminish the base case PPD value to enhance occupant satisfaction while concurrently reducing energy consumption and carbon emissions. Consequently, the implementation of retrofit strategies outlined in section 7.5 led to a reduction in PPD values from 14.68% during post-retrofitting. Table 8.1 evaluates the reductions in occupant dissatisfaction with the implementation of individual retrofit measures.

Table 8.1: Social sustainability analysis with individual retrofit measures during the post-retrofitting stage.

Retrofit measures	PPD (%)	Change of occupant dissatisfaction (%)
Base Case	14.68	
Wall insulation		
25 mm thick (0.544 W/m^2k)	14.12	3.81
50 mm thick (0.4705 W/m^2k)	13.95	4.97
75 mm thick (0.392 W/m^2k)	13.92	5.18
100 mm thick (0.306 W/m^2k)	13.89	5.38
Wall shading		
100 mm	13.99	4.70
200 mm	13.97	4.84
300 mm	13.94	5.04
400 mm	13.92	5.18
Windows retrofitting		
4-4 mm thick glass with PVC frame (4.302 W/m^2k)	13.93	5.11
6-6 mm thick glass with PVC frame (4.239 W/m^2k)	13.92	5.18
4-4-4 mm thick glass with PVC frame (3.746 W/m^2k)	13.90	5.31

6-6-6 mm thick glass with PVC frame (3.678 W/m^2k)	13.87	5.52
Replacement of air conditioner		
Grade 1, 8530 BTU/h cooling capacity, 770 W power consumption	14.68	0.00
PV panel installation	14.68	0.00

According to Table 8.1, there is no significant change in the occupant's dissatisfaction with the replacement of the air conditioner and the installation of PV panels. Since the energy used for cooling is changed with the replacement of the air conditioner, there was no significant change in the PPD. Furthermore, the installation of PV panels, which primarily serve as an extra energy-generating source (Liu, 2015), did not significantly alter the building's comfort levels. Studies have indicated that by decreasing the U-values of building materials, buildings can offer improved thermal comfort by minimizing heat loss during winter and heat gain during summer (Yu et al., 2024). As a result, increasing insulation thickness, shading lengths, and glass thicknesses, PPD values have decreased significantly, indicating improved thermal comfort within buildings.

The details of the first five ranked retrofit strategies with the lowest PPD are represented in Table 8.2.

Table 8.2: First five ranked retrofit strategies with the lowest occupant dissatisfaction.

Wall insulation (thickness (mm))	Wall shading (length (mm))	Glass thickness of windows (mm)	Replacement of air conditioner	Number of PV panels	PPD (%)
100	400	4-4	No replacement	All options (from 0 to 14 PV panels)	13.74
100	400	6-6	No replacement	All options (from 0 to 14 PV panels)	13.74
100	400	4-4-4	No replacement	All options (from 0 to 14 PV panels)	13.75
100	400	4-4	Replaced	All options (from 0 to 14 PV panels)	13.75
100	400	6-6	Replaced	All options (from 0 to 14 PV panels)	13.75

According to Table 8.2, considering retrofit strategies, the lowest PPD value (13.74%) was indicated with the implementation of a retrofit strategy consisting of 100mm thick wall insulation, 400mm length wall shading, and 4-4mm/ 6-6mm thick double-glazed window with PVC frames. EPS is a great insulation material due to its low coefficient of heat transmission (U-value), which is significantly lower than that of other materials, as well as its superior moisture resistance (Zhou, 2015). Therefore, EPS plays an essential role in increasing occupant satisfaction by providing improved thermal properties in Hong Kong residential buildings. In addition, window glazing is a critical component of the building envelopes in enhancing thermal comfort, as it serves as a primary source of heat gain and heat transfer within buildings. Heat transmittance through windows is approximately five times greater than that through other building envelope components (Bülow-Hübe, 2001). Consequently, window glazing plays a significant role in regulating indoor thermal conditions. In colder climates, glazing with a lower U-value is recommended to minimize heat loss, whereas in warmer climates, glazing with a lower heat gain coefficient is preferable to enhance occupant comfort in residential buildings (He et al., 2021a). However, in subtropical regions, both solar control and heat transfer (U-value) must be considered to maintain optimal indoor comfort levels (Clarke et al., 1998). The findings of this study further highlight that the retrofit strategy yielding the lowest PPD occupants involves the use of double glazing with 4mm and 6mm glass thicknesses, rather than triple glazing, which exhibits higher heat transference (U-value). Additionally, the effectiveness of external wall shading in preventing solar radiation from entering the building significantly contributes to enhancing indoor thermal comfort. Given the climatic conditions of subtropical regions, the implementation of external wall shading is essential for maintaining comfortable indoor environments in residential buildings. Further, results highlighted that even though there was no significant change in the PPD with the replacement of the air conditioner, small changes in the PPD occurred when it was implemented with other retrofit measures. However, finally, all the retrofit strategies were aligned with social sustainability by representing lower PPD values compared with the base case.

8.2.2 Environmental Sustainability

In this study, carbon saving was considered the primary factor in assessing environmental sustainability. When calculating carbon savings, it is essential to account for the embodied carbon of retrofit materials in addition to operational carbon emissions. A retrofitted residential building that achieves NZC status in terms of operational energy may not necessarily meet NZC criteria when the embodied carbon of retrofit materials is not considered. To attain a truly NZC building, it is crucial to evaluate the impact of embodied carbon of retrofit materials and address it through carbon offsetting (UKGBC, 2019). The embodied carbon emissions associated with the retrofit materials for each retrofit strategy over their whole life will be evaluated using LCA (RICS, 2017). According to RICS, LCA calculations encompass various stages of a material's life cycle: product [A1–3], construction process [A4–5], use [B1–5], and end-of-life [C1–4] stages. Given the relatively minor carbon emissions stemming from the retrofit materials during the end-of-life (Dauletbek & Zhou, 2022), this aspect was disregarded in the estimation of embodied carbon. Following the boundary considered by Seo and Foliente (2021), this study considered the stages from A1-A5 and B4 (Figure 8.1) in calculating the embodied carbon associated with retrofit materials.

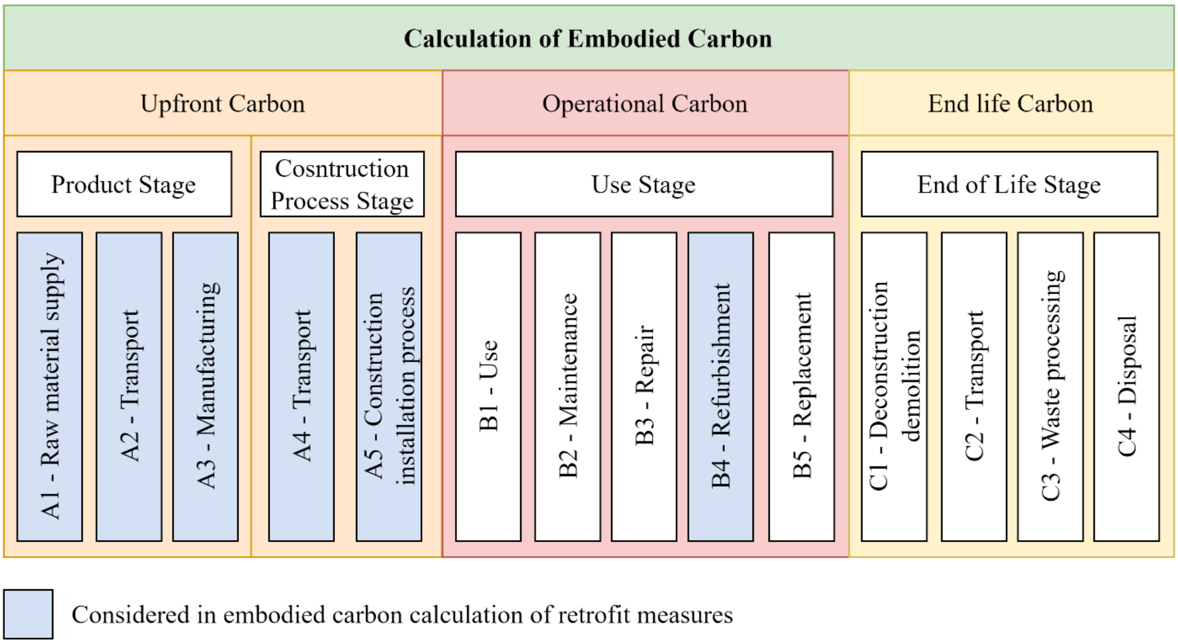


Figure 8.1: Stages considered in calculating the embodied carbon of retrofit materials.

One-click LCA software, a prevalent tool utilized for calculating embodied carbon, was employed in determining the embodied carbon associated with retrofit measures (section 3.7.3.1). Within these calculations, all materials were allocated through the software, with the location parameter set to the specified case study to compute carbon quantities linked to transportation. The study also made assumptions regarding the daily working hours, spanning from 8.00 am to 5.30 pm, for construction and refurbishment undertakings. Moreover, a drill with a power rating of 0.46 kWh was presumed to be utilized during insulation, shading, and window retrofitting activities. Accordingly, Table 8.3 illustrates the embodied carbon associated with individual retrofit measures.

Table 8.3: Embodied carbon of individual retrofit measures.

Retrofit measure	Embodied carbon ($kgCO_2e/m^2$)
Wall insulation	
25 mm thick (0.544 W/m^2k)	6.059
50 mm thick (0.4705 W/m^2k)	9.242
75 mm thick (0.392 W/m^2k)	12.434
100 mm thick (0.306 W/m^2k)	15.627
Wall shading	
100 mm	0.072
200 mm	0.117
300 mm	0.155

400 mm	0.202
Windows	
4-4 mm thick glass with PVC frame (4.302 W/m^2k)	3.045
6-6 mm thick glass with PVC frame (4.239 W/m^2k)	4.516
4-4-4 mm thick glass with PVC frame (3.746 W/m^2k)	4.537
6-6-6 mm thick glass with PVC frame (3.678 W/m^2k)	6.746
Air Conditioner	
Grade 1, 8530 BTU/h cooling capacity, 770 W power consumption	16.818
PV panel installation	
1 panel	4.550
2 panels	6.794
3 panels	9.620
4 panels	11.875
5 panels	14.701
6 panels	16.945
7 panels	19.761
8 panels	22.016
9 panels	24.832
10 panels	27.087
11 panels	29.341
12 panels	31.586
13 panels	33.841
14 panels	36.085

In addition to embodied carbon, the annual operational carbon emissions of the residential building were assessed through a case study model simulation using IESVE software. A total of 3,735 simulations were conducted in IESVE to evaluate operational carbon emissions and energy consumption following the implementation of various retrofit strategies in the case study building. Subsequently, Equations 5 and 6 (section 3.7.3.1) were employed to calculate both annual and lifetime carbon savings resulting from the retrofit interventions. In terms of the building's post-retrofitting lifespan, it is recognized that the extended usability of the building after retrofitting should not exceed the normal duration expected of a new building of a similar sort. According to Dauletbek and Zhou (2022), retrofitting techniques are unlikely to appreciably extend the building's service life beyond that of a newly constructed building. Hence, in determining lifetime carbon savings, the building's post-retrofit lifespan was assumed to be 30 years (Regulations, 2012). The details of carbon savings associated with individual retrofit measures, considering both operational and embodied carbon, are presented in Table 8.4.

Table 8.4: Environmental sustainability analysis with individual retrofit measures during the post-retrofitting stage.

Retrofit measure	Annual carbon emissions ($kgCO_2$)	Embodied carbon ($kgCO_2e$)	Annual carbon saving ($kgCO_2$)	Lifetime carbon saving ($kgCO_2$)	Percentage of carbon saving (%)
Base case	1,384.5				
Wall insulation					
25 mm thick (0.544 W/m^2k)	1,375.2	145.05	4.46	133.95	0.32
50 mm thick (0.4705 W/m^2k)	1,369.6	221.25	7.53	225.75	0.54
75 mm thick (0.392 W/m^2k)	1,360.7	297.67	13.88	416.33	1.00
100 mm thick (0.306 W/m^2k)	1,358.3	374.11	13.73	411.89	0.99
Wall shading					
100 mm	1,383.8	1.71	0.64	19.29	0.05
200 mm	1,382.9	2.80	1.51	45.20	0.11
300 mm	1,381.7	3.71	2.68	80.29	0.19
400 mm	1,380.7	4.84	3.64	109.16	0.26
Windows					
4-4 mm thick glass with PVC frame (4.302 W/m^2k)	1,381.9	72.90	0.17	5.10	0.01
6-6 mm thick glass with PVC frame (4.239 W/m^2k)	1,379.5	108.11	1.40	41.89	0.10
4-4-4 mm thick glass with PVC frame (3.746 W/m^2k)	1,378.7	108.62	2.18	65.38	0.16
6-6-6 mm thick glass with PVC frame (3.678 W/m^2k)	1,364.8	161.50	14.32	429.50	1.03
Air Conditioner					
Grade 1, 8530 BTU/h cooling capacity, 770 W power consumption	1,261.2	402.62	109.88	3,296.38	7.94
PV panel installation					
1 panel	1,198.1	108.92	182.77	5,483.08	13.20
2 panels	1,011.8	162.65	367.28	11,018.35	26.53
3 panels	825.6	230.30	551.22	16,536.70	39.81
4 panels	639.4	284.29	735.62	22,068.71	53.13
5 panels	453.1	351.94	919.67	27,590.06	66.43
6 panels	266.9	405.66	1,104.08	33,122.34	79.75
7 panels	80.6	473.08	1,288.13	38,643.92	93.04
8 panels	-105.6	527.06	1,472.53	44,175.94	106.36
9 panels	-291.8	594.48	1,656.48	49,694.52	119.64
10 panels	-478.1	648.46	1,840.98	55,229.54	132.97
11 panels	-664.3	702.42	2,025.39	60,761.58	146.29
12 panels	-850.6	756.17	2,209.89	66,296.83	159.62
13 panels	-1,036.8	810.15	2,394.29	71,828.85	172.94
14 panels	-1,223.0	863.87	2,578.70	77,361.13	186.26

As presented in Table 8.4, the highest carbon savings were achieved through the installation of PV panels. Since solar energy can generate electricity without direct carbon emissions, the integration of PV panels enables buildings to significantly reduce their operational carbon emits through energy consumption (Y. Wang et al., 2014). Furthermore, when considering individual retrofit measures, wall insulation, shading, and window retrofitting, the findings indicate that the highest carbon savings were achieved using 75 mm thick insulation, 400mm wide external shading, and 6mm thick triple-glazed windows with PVC frames, respectively. These results highlight that carbon savings vary depending on parameters within the same retrofit category. Additionally, the replacement of the air conditioning system resulted in a 7.94% reduction in carbon emissions, demonstrating a greater impact compared to building envelope upgrades.

Table 8.5 represents the details of the first five-ranked retrofit strategies with the highest carbon saving.

Table 8.5: First five ranked retrofit strategies with higher carbon savings.

Wall insulation (thickness (mm))	Wall shading (length (mm))	Glass thickness of windows (mm)	Replacement of air conditioner	Number of PV panels	Annual energy consumption per area (kWh/m^2)	Annual carbon emission ($kgCO_2$)	Embodied carbon ($kgCO_2e$)	Annual carbon saving ($kgCO_2$)
75	400	6-6-6	Replaced	14	-1,21.5	-1,391.1	1,730.503	2,717.917
100	400	6-6-6	Replaced	14	-1,22.4	-1,393.5	1,806.943	2,717.769
75	300	6-6-6	Replaced	14	-1,20.3	-1,390.1	1,729.378	2,716.954
100	300	6-6-6	Replaced	14	-1,21.2	-1,392.5	1,805.818	2,716.806
75	no	6-6-6	Replaced	14	-1,15.4	-1,388.9	1,725.667	2,715.878

According to Table 8.5, the strategy consisting of 75mm thick insulation had the highest carbon saving, while the strategy with 100mm thick insulation emerged as the second most carbon-saving approach. Despite the operational carbon emission saving achieved through the retrofitting with 100mm thick insulation, its corresponding embodied carbon surpasses that of the 75mm thick insulation retrofit. When assessed based on energy conservation, these retrofit strategies exhibited a reordering of their rankings, with the 100mm thick insulation strategy leading in energy savings, while the 75mm thick insulation strategy followed closely. This disparity underscores the divergence between zero-energy and zero-carbon residential buildings, emphasizing the significance of considering the embodied carbon content of retrofit materials in the pursuit of NZC buildings. Moreover, all retrofit strategies were aligned with environmental sustainability objectives by yielding positive carbon savings (as per Equations 5 and 6) compared to the base case.

8.2.3 Economic Sustainability

In this study, economic sustainability in the post-retrofit phase was evaluated using economic profitability as a key metric. Equations 1 to 4 in section 3.7.3.2 were applied to compute both annual and lifetime economic profitability. These equations necessitated the calculation of the initial cost of retrofit materials and energy costs to determine economic profitability accurately. Hence, to ascertain the cost of retrofit materials, a market survey was conducted over three months via online platforms such as Alibaba, Fortress, Wealth Bridge Co.Ltd, and RS Components. The mean prices of these measures are presented in Table 8.6.

Table 8.6: Data obtained on the cost of retrofit measures through the market survey.

Retrofit measure	Initial investment cost (HKD)
Wall insulation	
25 mm thick	20.83 (per m^2)
50 mm thick	42.18 (per m^2)
75 mm thick	65.18 (per m^2)
100 mm thick	88.08 (per m^2)
Wall shading	
Concrete	1650.17 (per m^3)
Windows	
4-4 mm thick glass with PVC frame	752.06 (per one window)
6-6 mm thick glass with PVC frame	1,256.19 (per one window)
4-4-4 mm thick glass with PVC frame	1,727.31 (per one window)
6-6-6 mm thick glass with PVC frame	1,884.28 (per one window)
Air Conditioner	
Grade 1, 8530 BTU/h cooling capacity, 770 W power consumption	4,750.00
PV panel installation	
1.6 m x 1.0m monocrystalline PV panel	2,987.31 (per one panel)

Additionally, in calculating the energy costs, the residential electricity rates in Hong Kong were taken into consideration. According to information from HKElectric (2024), the pricing structure involves a rate of 0.779 HKD for the initial 150 units, escalating to 0.918 HKD and

1.057 HKD for consumption levels between 151-300 units and 301-500 units, respectively. Given that the energy consumption of the selected building surpasses the threshold of 200 and 300 units, the average rate of 0.918 HKD was employed as the representative energy cost for this study. Table 8.7 represents the evaluation of economic profitability using equations from 1 to 4 (section 3.7.3.2), considering individual retrofit measures.

Table 8.7: Economic sustainability analysis with individual retrofit measures during the post-retrofitting stage.

Retrofit measure	Annual Energy Consumption per area (kWh/m^2)	Initial investment cost (HKD)	Annual energy saving (kWh)	Annual economic profitability (HKD)	Lifetime economic profitability (HKD)
Base case	111.4				
Wall insulation					
25 mm thick (0.544 W/m^2k)	111.0	503.04	9.58	-7.98	-239.32
50 mm thick (0.4705 W/m^2k)	110.8	1,018.65	14.36	-20.77	-623.07
75 mm thick (0.392 W/m^2k)	110.2	1,574.10	28.73	-26.10	-782.93
100 mm thick (0.306 W/m^2k)	109.3	2,127.13	50.27	-24.75	-742.58
Wall shading					
100 mm	110.4	9.41	23.94	21.66	649.90
200 mm	108.7	18.81	64.64	58.71	1,761.32
300 mm	106.3	28.22	122.09	111.14	3,334.25
400 mm	105.1	37.62	150.82	137.20	4,116.02
Windows					
4-4 mm thick glass with PVC frame (4.302 W/m^2k)	110.2	3,008.24	28.73	-73.90	-2,217.07
6-6 mm thick glass with PVC frame (4.239 W/m^2k)	108.7	5,024.76	64.64	-108.15	-3,244.63
4-4-4 mm thick glass with PVC frame (3.746 W/m^2k)	108.2	6,909.24	76.61	-159.98	-4,799.46
6-6-6 mm thick glass with PVC frame (3.678 W/m^2k)	105.6	7,537.12	138.85	-123.77	-3,713.14
Air Conditioner					
Grade 1, 8530 BTU/h cooling capacity, 770 W power consumption	101.5	4,750.00	237.01	59.24	1,777.15
PV panel installation					
1 panel	96.4	2,987.31	359.10	230.08	6,902.30
2 panels	81.5	5,974.62	715.81	457.96	13,738.68
3 panels	66.5	8,961.93	1,074.91	688.03	20,640.98

4 panels	51.5	11,949.24	1,434.01	918.11	27,543.29
5 panels	36.5	14,936.55	1,793.11	1,148.19	34,445.59
6 panels	21.5	17,923.86	2,152.21	1,378.26	41,347.89
7 panels	6.5	20,911.17	2,511.31	1,608.34	48,250.20
8 panels	-8.5	23,898.48	2,870.41	1,838.42	55,152.50
9 panels	-23.5	26,885.79	3,229.51	2,068.49	62,054.81
10 panels	-38.5	29,873.10	3,588.61	2,298.57	68,957.11
11 panels	-53.5	32,860.41	3,947.71	2,528.65	75,859.41
12 panels	-68.5	35,847.72	4,306.81	2,758.72	82,761.72
13 panels	-83.5	38,835.03	4,665.91	2,988.80	89,664.02
14 panels	-98.5	41,822.34	5,025.01	3,218.88	96,566.33

In accordance with the findings presented in Table 8.7, retrofitting endeavors involving singular measures such as wall insulation and double or triple-glazed windows with PVC frames do not demonstrate economic viability on an individual basis. Despite their capacity to yield energy savings when implemented independently, these measures do not prove to be economically feasible. Conversely, retrofitting with external wall shadings emerges as a financially advantageous option due to its lower initial cost, resulting in heightened economic profitability. Moreover, the installation of PV panels is associated with higher initial costs; however, it offers substantial economic benefits owing to its capacity to generate surplus energy, thereby facilitating additional financial gains (Lee & Shepley, 2020). To mitigate the initial expenditure linked with PV panel installation in residential buildings, the Hong Kong government has implemented tax incentives aimed at reducing capital outlays incurred in deploying renewable energy systems on private premises (GovHK, 2024b). Additionally, the government has introduced a "Feed-in Tariff" scheme to incentivize private entities to install PV panels, enabling building occupants to sell excess energy to utility companies, thereby generating supplementary income and recouping investments in PV installation (GovHK, 2024c). While Table 8.7 above evaluates the economic sustainability of individual retrofit measures, Table 8.8 provides details of the top five retrofit strategies ranked based on their economic profitability.

Table 8.8: First five ranked retrofit strategies with the highest economic profitability.

Wall insulation (thickness (mm))	Wall shading (length (mm))	Glass thickness of	Replacement of air conditioner	Number of PV panels	Annual energy saving (kWh)	Initial investment cost (HKD)	Annual economic profitability (HKD)	Lifetime economic profitability (HKD)

		windows (mm)						
25	400	No	Replaced	14	5,415.23	47,113.00	3,400.75	102,022.38
No	400	No	Replaced	14	5,384.11	46,609.96	3,388.94	101,668.32
50	400	No	Replaced	14	5,420.02	47,628.61	3,387.95	101,638.63
100	400	No	Replaced	14	5,455.93	48,737.09	3,383.97	101,519.11
75	400	No	Replaced	14	5,434.38	48,184.06	3,382.63	101,478.77

As depicted in Table 8.8, the absence of window retrofitting measures within the strategies identified as possessing the highest economic profitability is notable. The significant initial investment cost associated with window retrofitting has evidently influenced the economic viability of the overall retrofit measures. Consequently, the analysis based on the initial costs of retrofit measures reveals a mix of retrofit strategies with economic profits as well as losses. Moreover, the observation that the highest economic profitability strategies incorporate a maximum number of PV panels underscores the potential for maximizing financial gains through the utilization of renewable energy sources, renowned for their robust energy generation capabilities (Osman et al., 2023).

However, the outcomes of the assessments focusing on social, environmental, and economic sustainability reveal a diverse performance among the retrofit strategies concerning PPD, carbon savings, and economic profitability. Consequently, determining the most sustainable retrofit strategies based on these varied criteria poses a significant challenge. As a result, the implementation of a multi-objective optimization approach is deemed necessary to identify the optimal retrofit strategies that exhibit superior performance across PPD, carbon savings, and economic profitability metrics. This optimization process aims to ascertain whether the selected retrofit strategies align effectively with social, environmental, and economic sustainability objectives. Thus, the following chapter will delve into the multi-objective optimization process to determine the alignment of the retrofit strategies with sustainable features.

8.3 Chapter Summary, Contributions, and Limitations

The primary aim of retrofitting existing residential buildings towards NZC status is to achieve social, environmental, and economic sustainability. While existing literature has extensively examined these three dimensions of sustainability either in isolation or in pairs, limited attention has been given to their holistic assessment. This chapter addressed this gap by evaluating the social, environmental, and economic sustainability aspects of the retrofit strategies developed in Chapter 7. To assess energy consumption, carbon emissions, and PPD during the post-retrofit stage, the case study model was simulated using the IESVE software. Additionally, the OneClick tool was utilized to quantify the embodied carbon associated with the retrofit measures. A comprehensive market survey was carried out to determine the initial investment costs of the retrofit measures. Subsequently, the equations outlined in section 3.7.2 were applied to analyze the social, environmental, and economic sustainability during the post-retrofit phase. The findings revealed that the performance of the retrofit strategies varied across PPD, carbon savings, and economic profitability metrics. While all strategies exhibited favorable outcomes in terms of social and environmental sustainability, characterized by reduced PPD and positive carbon savings compared to the base case, they demonstrated varying levels of economic profitability, representing profits as well as losses.

The outcomes of this chapter hold significant value for academic and industry professionals. Researchers can leverage these findings to enhance the depth of sustainability analyses conducted on retrofit strategies, thus enriching their future studies. Furthermore, the insights from this chapter can serve as a foundation for the formulation of sustainable retrofit strategies in various research endeavors. Industry practitioners stand to gain valuable insights from these findings, empowering them to make informed decisions regarding the social, environmental, and economic sustainability dimensions of retrofit measures. Moreover, policymakers can utilize the findings of this study to inform the development of policies aimed at improving social, environmental, and economic sustainability when retrofitting existing residential buildings to NZC.

While this chapter makes valuable contributions to both academic and industry practitioners, it is essential to acknowledge several limitations. The scope of this chapter was confined to residential buildings in Hong Kong, thereby limiting the generalizability of the findings. Additionally, the methodology employed in this chapter relied on outcomes from annual model simulations to estimate lifetime performances, without conducting separate simulations over the entire lifespan of the retrofits. Future research endeavors could address these limitations by conducting an array of simulations using diverse weather files to comprehensively assess energy consumption, carbon emissions, and PPD across the post-retrofit stage. Furthermore, the chapter did not account for end-of-life considerations of retrofit materials in calculating embodied carbon, and the profitability calculations were based on a simplistic equation that did not incorporate inflation rates. Subsequent studies could aim to overcome these limitations by integrating consideration of all the stages during embodied carbon calculations and by accounting for inflation rates in calculating economic profitability. Despite these limitations, the insights gathered from this chapter would have the potential to significantly contribute to the creation of a zero-carbon built environment.

CHAPTER NINE

9.0 Development of a Model to Make Optimal Decisions Concerning Social, Environmental, and Economic Sustainability while Retrofitting Residential Buildings to NZC

9.1 Introduction

Chapters 6, 7, and 8 evaluated different retrofit measures, formulated retrofit strategies, and analyzed their social, environmental, and economic sustainability features. The primary objective of this chapter is to develop a model to make optimized decisions on residential building NZC retrofitting focusing on social, environmental, and economic sustainability. In pursuit of this objective, this chapter develops multi-objective optimization models, the implementation and validation of which are based on the data collected for the sustainability analysis of retrofit strategies using the selected case study (Chapter 7). Finally, this chapter automated the multi-objective optimization models through their deployment as a web application. This web application serves the purpose of aiding the selection of optimal retrofit strategies aimed at attaining NZC residential buildings while maximizing social (occupant satisfaction), environmental (carbon saving), and economic sustainability (economic profitability).

The development of the multi-objective optimization models was executed using Jupyter Notebook, incorporating three distinct algorithms: (1) NSGA II, (2) NSGA III, and (3) AGE-MOEA (section 3.8.2) to ensure the reliability and robustness of the model. The database developed by incorporating the post-retrofit data related to energy consumption, carbon emissions, and occupant dissatisfaction, as well as their embodied carbon and initial investment costs (Chapter 8), was used for the implementation and validation of the multi-objective optimization model. Finally, the Streamlit framework was utilized for deploying the multi-objective optimization model as a web application. Hence, this chapter contributes to the existing body of knowledge on residential building NZC retrofitting by introducing an automated model to decide the optimal retrofit strategies while enhancing the social, environmental, and economic sustainability features (occupant satisfaction, carbon saving, and economic profitability, respectively). Thus, this chapter could serve as a valuable resource for industry practitioners, stakeholders, and international organizations with an interest in the field of building retrofitting aimed at achieving NZC.

9.2 Development of Optimization Model

9.2.1 Principle of Optimization Model

An analysis that considers social, environmental, and economic dimensions is an important tool for determining energy-efficient, carbon-efficient, cost-effective, and occupant-satisfactory retrofit alternatives. Diverse quantitative methodologies have been employed to formulate optimization models aimed at delineating retrofit strategies contributing to the realization of zero-carbon and energy-efficient buildings. For instance, Seo and Foliente (2021) identified retrofit strategies for residential buildings in Metropolitan Melbourne, Australia, focusing on environmental sustainability through life cycle energy and carbon assessments, and economic sustainability via the calculation of payback periods to gauge financial benefits. Similarly, Dauletbek and Zhou (2022) conducted a study for residential buildings in Nanjing, evaluating life cycle cost, energy, and carbon assessments. Further, Halimov et al. (2020) developed an optimization model to decide retrofit strategies for residential buildings in Uzbekistan focusing on the minimization of primary energy consumption and investment costs. Accordingly, most of the studies have primarily focused on economic and environmental sustainability, frequently overlooking occupant satisfaction, which is a component of social sustainability. As a result, this chapter investigated social, environmental, and economic sustainability criteria for selecting retrofit strategies for residential buildings to achieve NZC.

The concept of carbon savings is fundamental to the environmental aspect, and it is a key factor in achieving NZC residential buildings. In this context, operational carbon emissions and the embodied carbon associated with retrofit solutions were used to assess environmental sustainability. Concurrently, economic profitability was used to determine economic sustainability, and the PPD was used to assess social sustainability. The focus of retrofitting efforts towards NZC is to minimize the carbon emissions from existing buildings, with the principal benefits of building retrofits reflecting lower energy usage and carbon emissions. This emphasizes the importance of NZC retrofit decisions in moving these goals ahead.

The optimization of carbon savings refers to an increase in building energy efficiency combined with a decrease in operational carbon emissions, which encompasses the primary goal of retrofitting residential buildings for NZC. The economic profitability of retrofitting residential buildings depends on the initial investment cost involved with the retrofit measures and savings due to the reduction in energy consumption, while the changes in PPD due to the retrofitting depend on the temperature variations in the building due to the implementation of retrofit measures. Accordingly, the combination of carbon savings, PPD, and economic profitability captures carbon reductions, occupant satisfaction, as well as the financial implications of retrofit measures that come with the residential building NZC retrofitting. Therefore, this study considers multi-objective optimization to decide optimal retrofit strategies focusing on occupant satisfaction (social sustainability), carbon saving (environmental sustainability), and economic profitability (economic sustainability) associated with the implementation of retrofit strategies. The current chapter focuses on two optimization models concerning the annual and lifetime performances of retrofit strategies.

9.2.2 Optimization Decision Objectives and Variables

Three key objectives highlight the optimization model in terms of social, environmental, and economic sustainability associated with the NZC retrofitting of residential buildings. Accordingly, minimum occupant dissatisfaction along with maximum carbon saving and economic profitability leads to optimal retrofit decisions by enhancing social, environmental, and economic sustainability in retrofitting residential buildings to NZC. The equations from 1 to 6 (section 3.7.3) were employed in calculating economic profitability and carbon saving.

However, the outcomes for the three objectives vary depending on the specific measures included in each retrofit strategy. Accordingly, changes in the selected retrofit solutions cause variations in energy consumption, carbon emissions, embodied carbon, and initial investment costs. As a result, the different retrofit measures identified from chapters 6 and 7; wall insulation, wall shading, window retrofitting, air conditioner replacement, and installation of PV panels, were treated as decision variables in the two optimization models. Hence, five decision variables along with three objectives were considered while developing the optimization model. When defining the boundaries for decision variables, the lower boundary was set to “0” to indicate the absence of a variable, and the upper limit was set to the number of different parameters under each variable.

9.2.3 Constraints

To fulfill the optimization objectives, the models must satisfy the constraints listed below.

Optimization model concerning the building’s lifetime performance

This model evaluates retrofit strategies based on cumulative performance over the building's operational lifetime, prioritizing long-term sustainability benefits. While this approach may not guarantee strict NZC compliance as defined by UKGBC (2019) annual criteria, it identifies the most sustainable solutions from a lifecycle perspective. The constraints are:

- Lifetime carbon saving ≥ 0
- Lifetime economic profitability ≥ 0
- PPD after retrofitting ≤ PPD base case

Optimization model concerning the building's annual performance

This model specifically targets NZC compliance by ensuring that retrofit strategies achieve zero or negative annual operational carbon emissions, aligned with the UKGBC (2019) definition. This model guarantees that identified solutions qualify as genuine NZC buildings. The first constraint in the annual model ensures that carbon reductions equal or exceed baseline emissions, accounting for both operational improvements and annualized embodied carbon impacts, thereby satisfying NZC requirements. The constraints are:

- Annual carbon saving ≥ Base case carbon emissions
- Annual economic profitability ≥ 0
- PPD after retrofitting ≤ PPD base case

9.3 Implementation and Validation of Optimization Models

After establishing the objectives, variables, and constraints, two unique models to optimize lifetime and annual performance were developed using three distinct optimization algorithms; (1) NSGA II, (2) NSGA III, and (3) AGE-MOEA. Three distinct optimization algorithms were used to ensure the reliability and robustness of the models. The case study used for the sustainability analysis of retrofit strategies was selected to implement the optimization model. Table 9.1 depicts the details of the base case used to implement and validate the optimization models.

Table 9.1: Details of the case study used for the implementation and validation of optimization models.

Characteristic	Details
Annual energy consumption	111.4 kWh/m^2
Annual carbon emission	1384.50 kgCO_2
PPD	14.68%
Floor area	23.94 m^2
Lifetime after retrofitting	30 years
Average energy cost	0.918 HKD

The data collected through case study simulations, embodied carbon calculations, and market surveys (Chapter 8) were implemented in the optimization models to validate their performances. Accordingly, a database consisting of 3735 retrofit strategies along with their energy consumption, carbon emissions, PPD, embodied carbon, initial investment costs, and the details of the base case was imported to the Jupyter Notebook to validate the performance of the optimization model. Upon performing calculations pertaining to carbon savings and economic profitability, the algorithms were executed with a population size of 100 over 100 iterations. Finally, after satisfying the specified constraints, the model provided optimized retrofit strategies aimed at achieving NZC residential buildings.

9.3.1 Results of Optimization Models

Although two distinct models were formulated to address varying constraints focusing on both annual and lifetime performance following building NZC retrofitting, the optimal solutions remained consistent across the selected case in both models. The outcomes of the two optimization models are shown in Table 9.2. Figures 9.1 and 9.2 show the Pareto fronts of optimal retrofit solutions derived from models of annual and lifetime performances after NZC retrofitting, respectively. In addition, two-dimensional plots of optimal solutions from models concerning annual and lifetime performances following NZC retrofitting are represented in Figures 9.3 and 9.4, respectively.

Table 9.2: Optimal retrofit solutions achieve NZC from existing residential buildings in Hong Kong.

No	Retrofit strategy					Annual carbon saving ($kgCO_2$)	Economic Profitability (HKD)	Lifetime carbon saving ($kgCO_2$)	Lifetime cost saving (HKD)	PPD	Algorithms		
	Wall insulation	Wall shading	Window retrofitting	Air conditioner	PV panels						NSGA II	NSGA III	AGE-MOEA
1	75mm	400mm	6-6-6 mm thick glass with PVC frame	No replacement	14	2,610.94	3,204.01	78,328.12	96,120.35	13.77	✓	x	✓
2	100mm	400mm	6-6-6 mm thick glass with PVC frame	No replacement	14	2,610.79	3,205.36	78,323.68	96,160.69	13.77	✓	✓	✓
3	100mm	400mm	4-4-4 mm thick glass with PVC frame	No replacement	14	2,605.65	3,166.95	78,169.56	95,008.44	13.75	✓	✓	✓
4	50mm	400mm	6-6-6 mm thick glass with PVC frame	No replacement	14	2,604.58	3,209.34	78,137.54	96,280.21	13.77	✓	x	✓
5	75mm	400mm	6-6 mm thick glass with PVC frame	No replacement	14	2,604.42	3,215.23	78,132.51	96,456.99	13.77	✓	✓	✓
6	25mm	400mm	6-6-6 mm thick glass with PVC frame	No replacement	14	2,601.52	3,222.13	78,045.74	96,663.96	13.78	✓	✓	✓
7	50mm	400mm	6-6 mm thick glass with PVC frame	No replacement	14	2,598.06	3,220.56	77,941.92	96,616.86	13.76	✓	✓	✓
8	100mm	400mm	6-6 mm thick glass with PVC frame	No replacement	14	2,597.87	3,216.58	77,936.07	96,497.34	13.74	✓	✓	✓
9	75mm	400mm	4-4 mm thick glass with PVC frame	No replacement	14	2,596.99	3,249.48	77,909.72	97,484.55	13.75	✓	✓	✓
10	100mm	400mm	4-4 mm thick glass with PVC frame	No replacement	14	2,596.84	3,250.83	77,905.28	97,524.90	13.74	✓	✓	✓
11	50mm	400mm	4-4 mm thick glass with PVC frame	No replacement	14	2,590.64	3,254.81	77,719.14	97,644.41	13.77	✓	✓	✓
12	25mm	400mm	4-4 mm thick glass with PVC frame	No replacement	14	2,587.58	3,267.61	77,627.34	98,028.16	13.76	✓	✓	✓

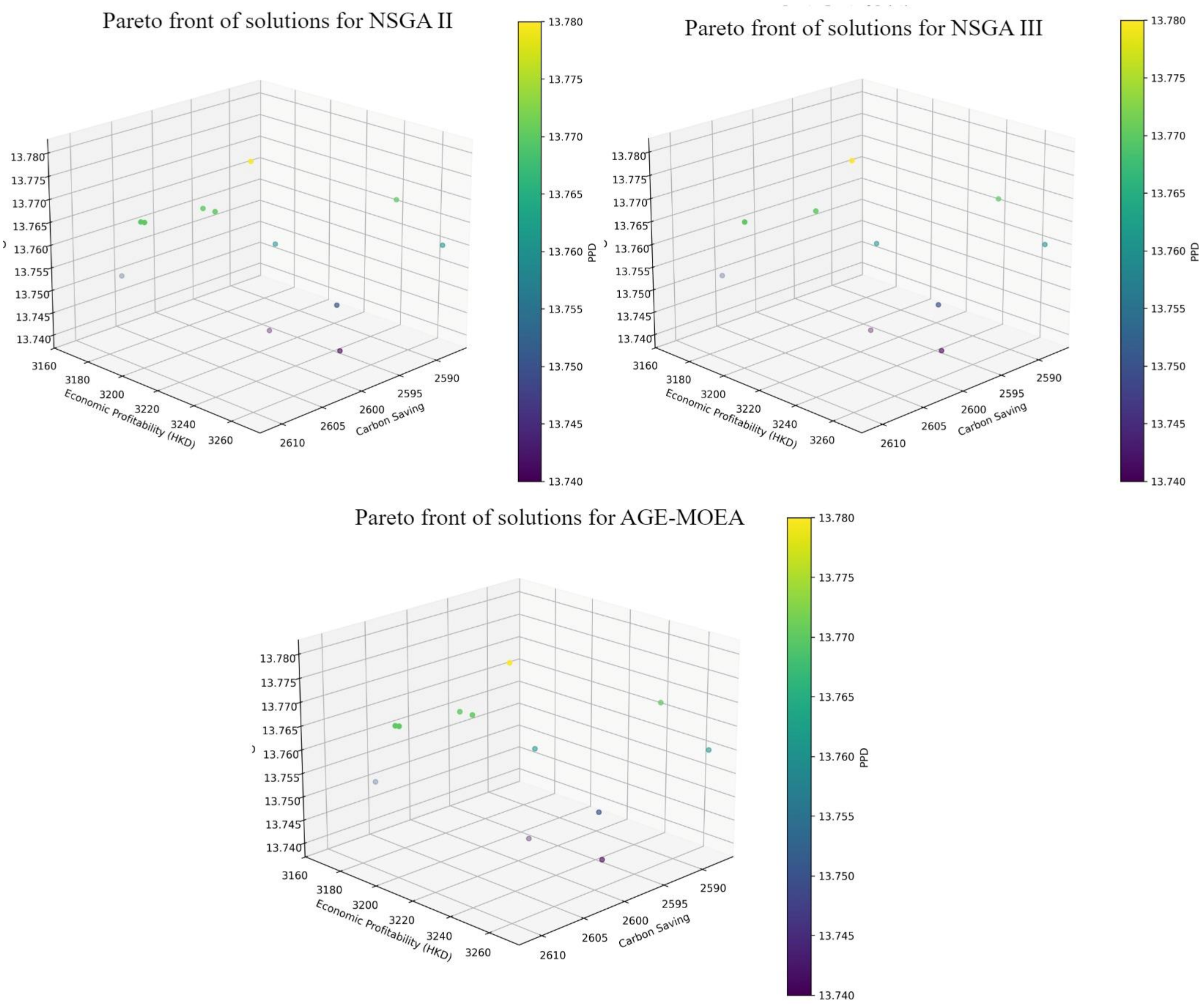


Figure 9.1: Pareto front of solutions from three distinct optimization algorithms in the model concerning the annual performance of the residential unit following the NZC retrofitting.

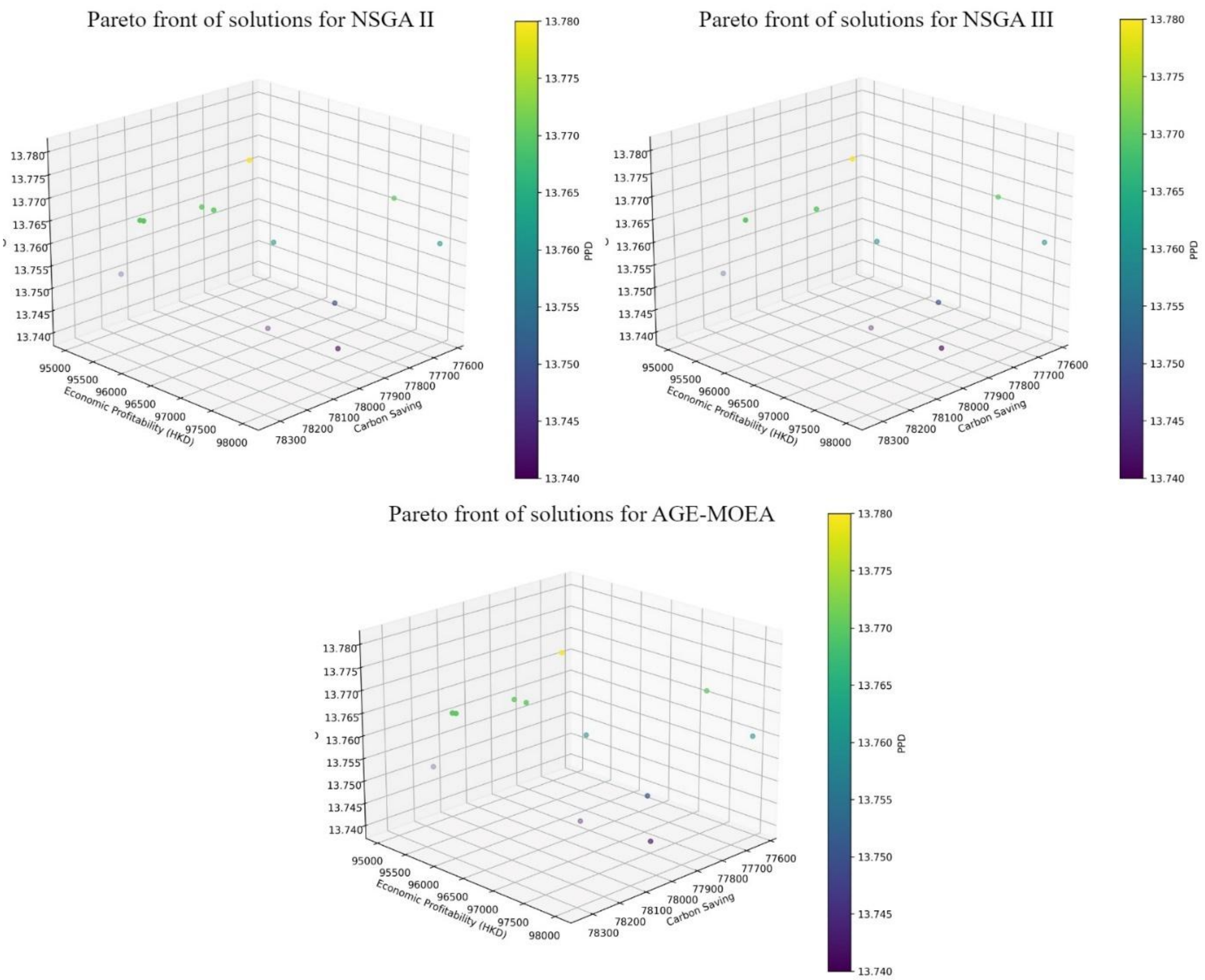


Figure 9.2: Pareto front of solutions from three distinct optimization algorithms in the model concerning the lifetime performance of the residential unit following the NZC retrofitting.

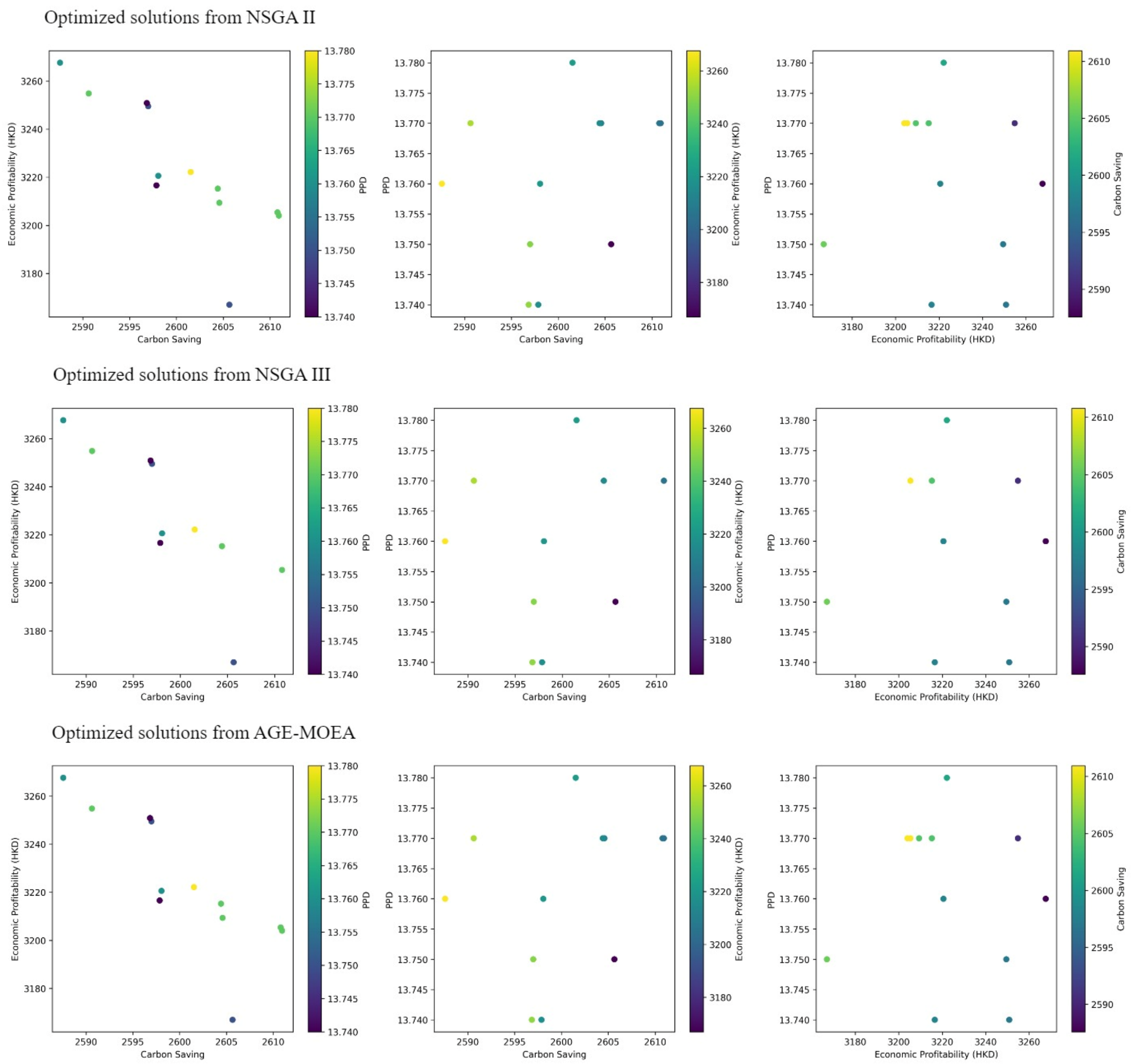


Figure 9.3: Two-dimensional mapping of optimized solutions against the objectives (from the model concerning annual performance).

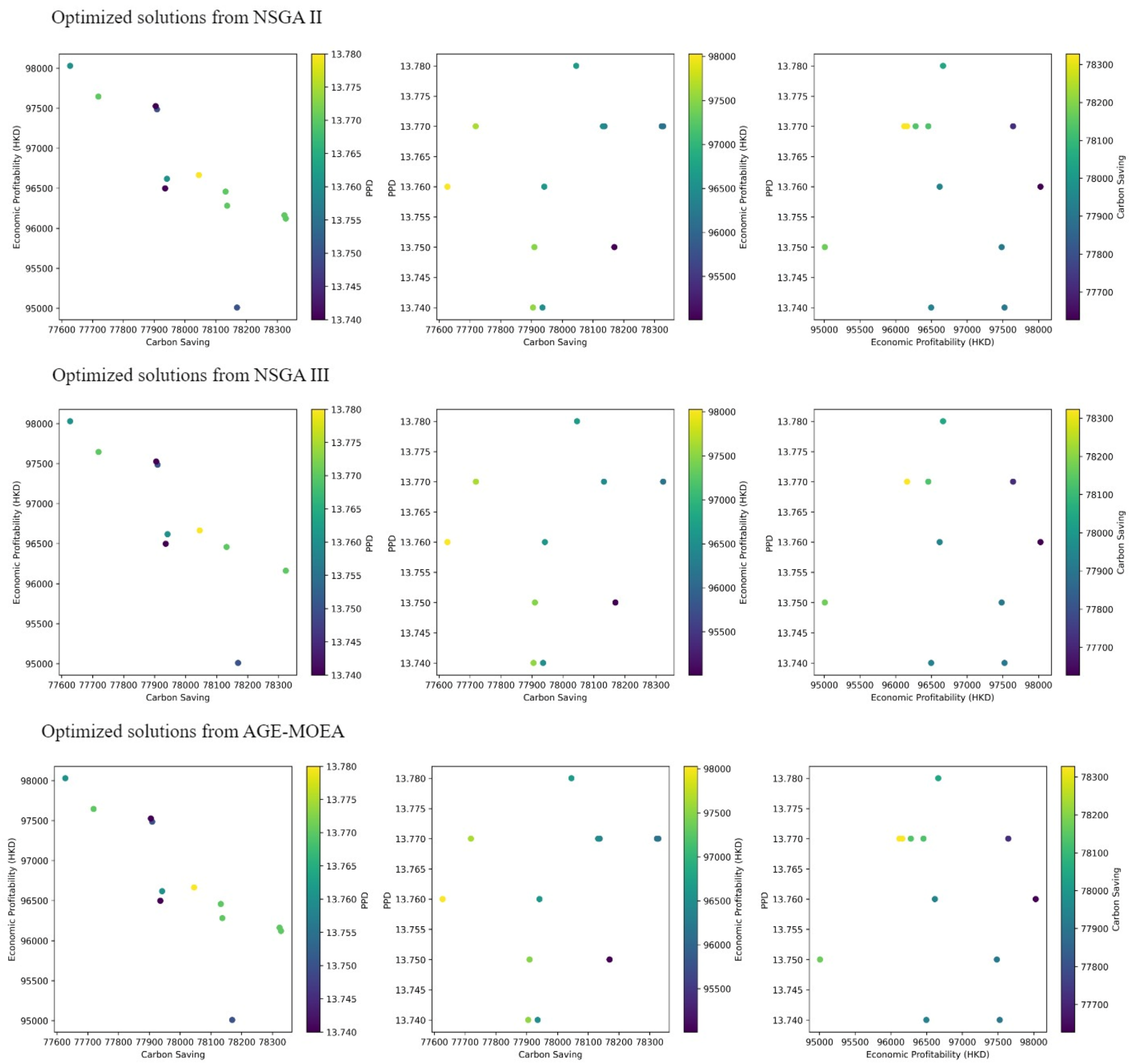


Figure 9.4: Two-dimensional mapping of optimized solutions against the objectives (from the model concerning lifetime performance).

As delineated in Table 9.2 and illustrated through Figures 9.1- 9.4, the algorithms NSGA II and AGE-MOEA provided 12 optimal solutions to enhance the social, environmental, and economic sustainability of the Hong Kong residential building NZC retrofitting. In contrast, NSGA III presented only 10 optimal solutions. The availability of a more diverse range of optimal operating conditions with NSGA III compared with NSGA II and AGE-MOEA (Chaudhari et al., 2022), could potentially contribute to variations in the number of outcomes produced by the three algorithms. Despite the different numbers of solutions obtained, the proposed strategies remained largely consistent across all three algorithms. This consistency in results across distinct algorithms serves to corroborate the reliability and robustness of the optimization models.

Furthermore, the findings underscored that each retrofit strategy yielded cost savings and carbon savings surpassing the baseline energy expenses and carbon emissions. Specifically, the cost savings exceeded the base case energy costs by percentages ranging from 129.36% to 133.47%, indicating high economic profitability, while carbon savings surpassed the base case emissions by percentages ranging from 186.90% to 188.58%. Additionally, the PPD metric indicated lower values, signifying reduced occupant dissatisfaction. These results suggest that the proposed solutions have the potential to attain the NZC residential buildings from the existing stock while enhancing the social, environmental, and economic sustainable features. However, in terms of ages and typologies, the results may be effectively performed within the individual residential units within multi-unit residential buildings in urbanized areas that were constructed decades ago, and the performance of identified measures may be different for the recently constructed buildings due to the use of sustainable materials and construction methods. In addition, the results may be effective for buildings which are having windows and sun-exposed walls.

9.3.2 Discussion of the Results

According to the aforementioned results, the optimized solutions proposed by both models exhibited similarities. Despite the examination of the annual and lifetime operational efficiencies of the residential building following NZC retrofitting, the data collection process included energy and carbon simulations for a single year rather than conducting distinct simulations spanning the building's projected 30-year lifespan. Consequently, the evaluation of the building's lifetime performance was conducted by extrapolating the annual energy consumption and carbon emission over 30 years (Ascione et al., 2019b; Luo, 2022; Seo &

Foliente, 2021). In light of that, this approach led to a lack of significant discrepancies between the optimal solutions offered by both models.

However, with the subtropical nature of Hong Kong, the strategies developed in Chapter 7 were used to determine the optimized solutions. The unique characteristics observed among the proposed optimized solutions include the utilization of maximum wall shading length, the incorporation of the highest number of PV panels, and the exclusion of air conditioner replacement. Notably, variations were identified in the parameters suggested for insulation thickness and window retrofitting within the optimized solutions. Among the optimal retrofit strategies to achieve NZC residential buildings in Hong Kong while achieving social, environmental, and economic sustainability, the following strategies represent the strategies with maximized carbon saving (188.58%), maximized economic profitability (133.47%), and minimized occupant dissatisfaction (6.40%), respectively.

- *Maximized carbon saving* - 75mm thick wall insulation, 400mm length wall shading, 6mm thick triple-glazed windows with PVC frame, and installation of 14 PV panels.
- *Maximized economic profitability* - 25mm thick wall insulation, 400mm length wall shading, 4mm thick double-glazed windows with PVC frame, and installation of 14 PV panels.
- *Minimized occupant dissatisfaction* - 100mm thick wall insulation, 400mm length wall shading, 6mm thick double-glazed windows with PVC frame, and installation of 14 PV panels, and 100mm thick wall insulation, 400mm length wall shading, 4mm thick double-glazed windows with PVC frame, and installation of 14 PV panels

Fundamental retrofitting strategies concerning buildings primarily revolve around enhancing envelope features like walls and windows (He et al., 2021b). Wall insulation stands out as a commonly employed retrofit measure aimed at curtailing heat transfer and solar heat gain into the building. Thicker insulation layers are instrumental in achieving a more substantial reduction in energy consumption and operational carbon emissions. Moreover, increased insulation thickness tends to correlate with lower levels of occupant dissatisfaction. Nevertheless, it is essential to acknowledge that thicker insulation materials come at a higher cost. The optimized solutions underscored that the retrofit strategy yielding the highest cost savings incorporated a 25mm thick insulation layer, while the strategy with the least cost saving featured a 100mm thick insulation layer. Climate-specific considerations necessitate varying thicknesses of wall insulation to regulate operational carbon emissions effectively. For instance, insulation thickness can range from 30mm to 60mm in southern China and 80mm -120mm in northern China (Zhu et al., 2011). In regions characterized by severe cold conditions, the typical insulation thickness ranges between 100mm and 140mm (He et al, 2021a). Notably, the average range of EPS insulation layers on external walls would be changed due to the varying wall materials (Zhang, 2017). Bojic et al. (2002) indicated that an insulation thickness of 50mm or higher in brick and concrete walls significantly contributes to reducing energy consumption in high-rise residential buildings in Hong Kong. However, the optimized solutions proposed a range of insulation thickness from 25mm to 100mm, in conjunction with wall shading, window retrofitting, and PV installation, as optimal strategies to achieve environmentally friendly, cost-effective, and occupant-satisfactory solutions for attaining NZC residential buildings in Hong Kong.

In accordance with prior research studies, solar heat gain emerges as a primary heat source affecting high-rise buildings in Hong Kong (Chen et al., 2015; Lam et al., 2010). Consequently, residential buildings in this region frequently contend with overheating issues attributed to the densely built urban landscape characterized by intense solar radiation and elevated air temperatures. Wall shading practices have gained prominence as a practical and cost-effective means to mitigate solar radiation exposure (Mandalaki et al., 2014). Studies have indicated that fixed external shading mechanisms generally outperform and offer greater cost efficiency compared to internal or manually adjustable counterparts (Valladares-Rendón et al., 2017). Therefore, the inclusion of fixed external wall shading measures within the optimal retrofit strategies is a logical choice. Based on the findings of the optimization process, a wall shading length of 400mm has been identified as optimal for achieving NZC within residential buildings in Hong Kong while simultaneously maximizing carbon savings, economic profitability, and minimizing occupant dissatisfaction. Following Practice Note for Authorized Persons APP-156 issued by the Hong Kong Buildings Department, external wall shading can extend up to 750mm from the wall, provided it does not pose safety hazards or obstructions. However, S. Liu et al. (2019) showed that enhancing energy efficiency and reducing operational carbon emissions in Hong Kong buildings is more effective when the spacing between wall shading elements is increased and the shading length is reduced compared to the 750mm limit. Additionally, S. Liu et al. (2019) propose an optimal spacing of 310mm between shading components for enhanced energy efficiency. Moreover, it has been observed that longer shading lengths effectively block direct solar radiation, allowing only diffuse radiation to reach the building walls (Tao et al., 2017). Consequently, the inclusion of 400mm wall shading lengths with 330mm spacing, within the optimal retrofit strategies, appears to be a viable approach for enhancing carbon savings, economic profitability, and occupant satisfaction while retrofitting existing residential buildings in Hong Kong to NZC.

Windows play a pivotal role in mitigating operational carbon emissions in existing buildings. The utilization of single-glazed windows in buildings, characterized by high U-values, signifies inadequate thermal efficiency, leading to elevated carbon emissions stemming from energy usage (He et al., 2021b). Beyond window type, the positioning of windows also influences the reduction of operational carbon emissions in existing buildings (He et al., 2021a). Double and triple-glazed windows predominantly contribute to decreasing operational carbon emissions by offering lower U-values compared to single-glazed windows, with the presence of air or gas insulation between the panes enhancing their efficacy (Chow et al., 2010). Consequently, these advanced window types facilitate diminished heat gain during summers and heat loss in winters, resulting in reduced operational carbon emissions (Gasparella et al., 2011). The adoption of double-glazed and triple-glazed windows is becoming increasingly prevalent in regions characterized by both cooling and heating dominance. He et al. (2021a) demonstrated that 6/12mm double-glazed windows and 6/15/6mm triple-glazed windows exhibit energy-efficient attributes in high-rise buildings situated in heating-dominated and cooling-dominated locales, with double-glazed windows proving to be more cost-effective than their triple-glazed windows. Harjunowibowo et al. (2019) underscored the energy-efficient features of 4/6mm double-glazed windows based on a case study conducted in the United Kingdom. Given Hong Kong's status as a cooling-dominant region, the utilization of 4mm and 6mm thick double and triple-glazed windows has shown promise in reducing carbon emissions while reducing occupant dissatisfaction compared to the base case. The optimization results advocate for the incorporation of 4mm and 6mm thick double-glazed as well as triple-glazed windows, alongside other retrofitting measures of wall insulation, shading, and PV installation, to maximize carbon savings, maximize economic profitability, and minimize occupant dissatisfaction while striving to achieve NZC in existing residential buildings in Hong Kong.

Regarding the air conditioner replacement, a significant disparity was noted between the proposed air conditioning unit and the existing one installed in the building, primarily concerning the British Thermal Unit (BTU). BTU serves as a measure of the energy consumed by air conditioning systems to extract heat from indoor air (McQuiston et al., 2023). Specifically, the prevailing air conditioner operated at 7000 BTU/h, while the proposed replacement unit featured a capacity of 8530 BTU/h. Efficient cooling system functionality hinges on aligning the BTU rating of the air conditioner with the floor area it serves. Ideally, an air conditioner with a BTU rating falling within the range of 7000 to 8000 BTU is recommended for areas spanning 250 sq.ft. to 350 sq.ft. (Bennett, 2025). Given that the selected case study entailed an area of 257.69 sq.ft. (23.94 m^2), the existing air conditioner was deemed more suitable than the proposed replacement in terms of efficiency. Consequently, despite the potential energy and carbon emission reductions associated with air conditioner replacement, this action was not endorsed within the optimal solutions could be due to the efficiency concerns with the BTU capacity and the floor area.

Utilizing renewable energy sources is imperative in the pursuit of NZC from existing buildings (Weerasinghe et al., 2024). In this context, the present study integrates monocrystalline PV panels installed on rooftops as a crucial element. The determination of the PV panel quantity was based on the building's floor area, with a maximum installation capacity of 14 panels. Optimal solutions aimed at maximizing carbon savings, economic profitability, and minimizing occupant dissatisfaction underscore the necessity of deploying the maximum number of PV panels on the rooftop. Consistent with these findings, previous research by Ascione et al. (2020) and Ascione et al. (2019b) emphasize the inclusion of extensive PV panel areas in optimal retrofit solutions to achieve zero-energy buildings. These studies focused on Mediterranean areas; Italy and Greece which have subtropical climates similar to Hong Kong, highlighting the effectiveness of rooftop PV installations in enhancing energy efficiency and cost-effectiveness. Rooftop PV panels exhibit the capacity to surpass the building's energy requirements, thereby aiding in reducing carbon emissions (Denholm & Margolis, 2008). According to the results of this study, despite the initial high costs associated with PV panel installations, the environmental and economic benefits they generate are substantial. Notably, the study revealed that maximal carbon and cost savings were attained through the installation of the greatest number of PV panels. While challenges related to the high-rise nature of buildings may impede rooftop PV panel installations, research by Peng and Lu (2013) elucidated that Hong Kong possesses significant rooftop areas suitable for PV panel deployment, with the potential to generate energy exceeding 10 times the building's requirements. Furthermore, Liang et al. (2024) asserted that rooftop PV panel installation is vital in achieving zero carbon emissions within Hong Kong.

Accordingly, the identified optimized retrofit solutions make social, environmental, and economic benefits through the residential building NZC retrofitting. Further, the optimized results have significant relevance in guiding decisions on sustainable NZC retrofitting policymaking as well as subsequent investments in achieving NZC in the existing residential buildings.

9.4 Deployment of the Automated Model to Make Optimized Decisions on Residential Building NZC Retrofitting

Following the execution of the optimization model utilizing NSGA II, NSGA III, and AGE-MOEA algorithms, the outcomes indicate that these three algorithms exhibit comparable efficacy in generating optimized solutions for residential building NZC retrofitting, thereby fostering social, environmental, and economic sustainability. Accordingly, the current study decided to incorporate all three algorithms for the deployment of an optimized decision-making model in the Streamlit framework.

The web application underwent segmentation into three distinct pages, each serving a specific purpose: the initial page designated for the home page, the second tailored for optimization pertaining to lifetime performances following NZC retrofitting (LCA optimization), and the third dedicated to optimization regarding annual performances after NZC retrofitting (Annual optimization). The navigation layout, depicted in Figure 9.5, facilitated a seamless transition between these pages. This split method improved the application's clarity and usability, allowing users to focus on their specific optimization needs without being distracted by unnecessary complications. In addition, there is a detailed user manual that describes the steps to follow while using the app, which is available to download from the home page.

Link to web application - https://building-retrofit-optimization-app.streamlit.app/

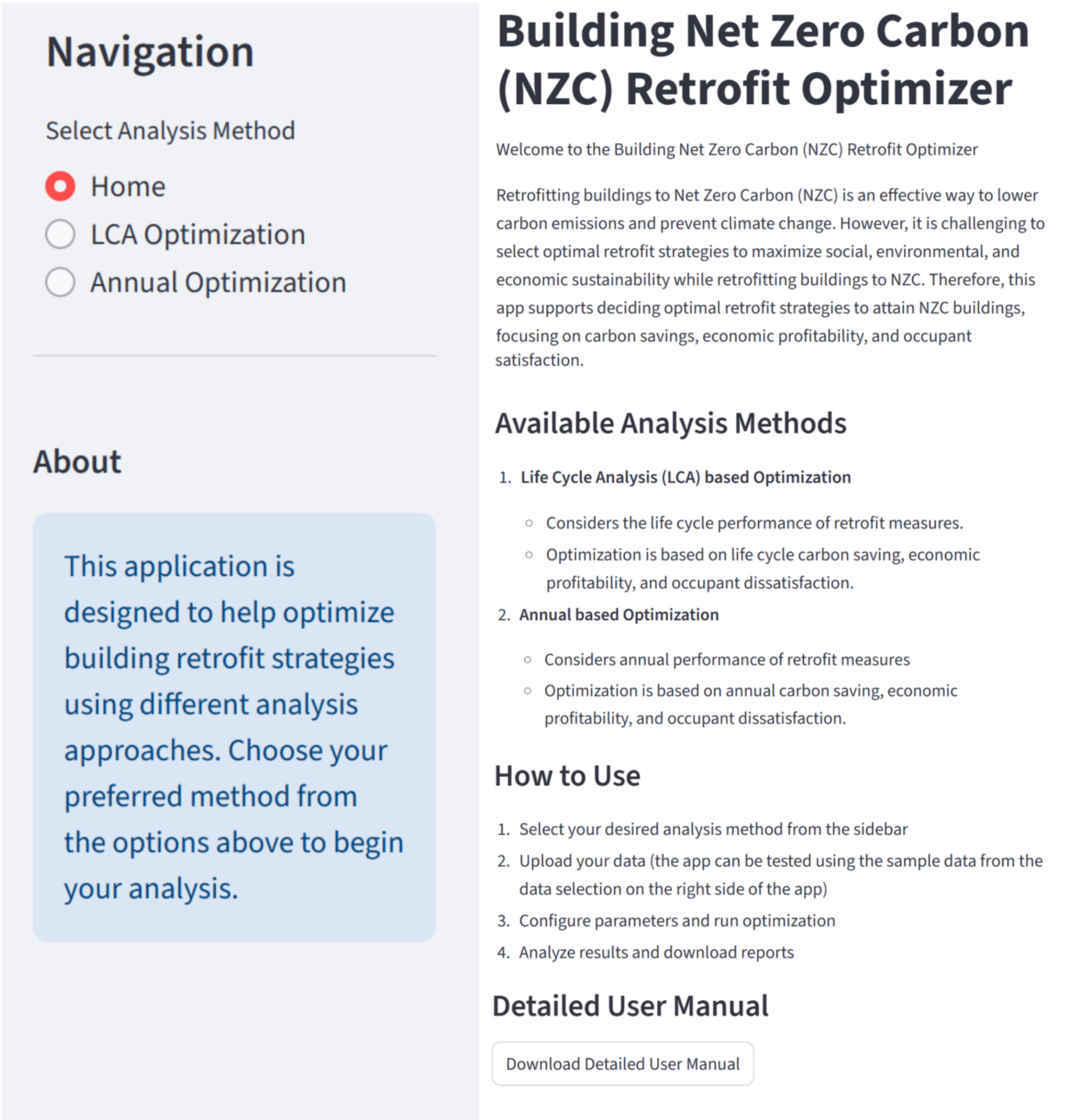


Figure 9.5: Navigation layout and the homepage.

In order to enhance user accessibility, the application was deployed on the Streamlit cloud platform. This cloud-based deployment avoided the necessity for users to execute the application locally, affording them a convenient web-based interface accessible from any internet-connected device. Even though the optimization model consisted of five variables, the web application was generalized to have several variables based on the user's requirements. In addition, the number of options under each variable is not limited to the number of options in the initial optimization model. Rigorous testing procedures were carried out utilizing two additional databases derived from the same case study to validate the application's efficacy, dependability, and responsiveness across a spectrum of different counts of retrofit measures. The deployment approach emphasized robust availability and fluid user interaction, guaranteeing the application's capacity to accommodate numerous simultaneous users without compromising optimization precision or operational speed.

9.4.1 Inputs to the Model

The user interface for the optimized decision-making model input was carefully designed to promote user-friendly interactions and smooth usability within the model. Despite encompassing two distinct models concerning annual and lifetime performances after building NZC retrofitting, the data input procedure was consistent to ensure coherence and ease of use throughout the model. Notably, data input necessitates separate entries through their respective designated pages. The user interface of this model integrates two distinct methods for data entry: (1) entry of fundamental details pertaining to the base case via the sidebar (left side of the app), and (2) submission of data related to retrofit strategies through an external file upload, selection of decision variables, and mapping the target columns in the datafile with the app description (right side of the app).

The sidebar of the user interface was designed to input basic details of the simulated building during the pre-retrofit stage (Figure 9.6). Accordingly, users can input details related to the parameters; energy consumption, carbon emissions, PPD, building's expected lifetime, energy cost per 1 kWh, and building area. These inputs hold significant importance as they directly impact the formulation of optimized decisions regarding building NZC retrofitting.

Furthermore, beyond these parameters, users are required to designate an algorithm from a selection comprising NSGA II, NSGA III, and AGE-MOEA. This feature empowers users to engage in an optimization process utilizing their preferred algorithms among the three, subsequently enabling them to contrast the outcomes derived from each algorithm. The incorporation of interactive elements such as sliders and dropdown menus serves to facilitate a smooth and precise data input experience for users.

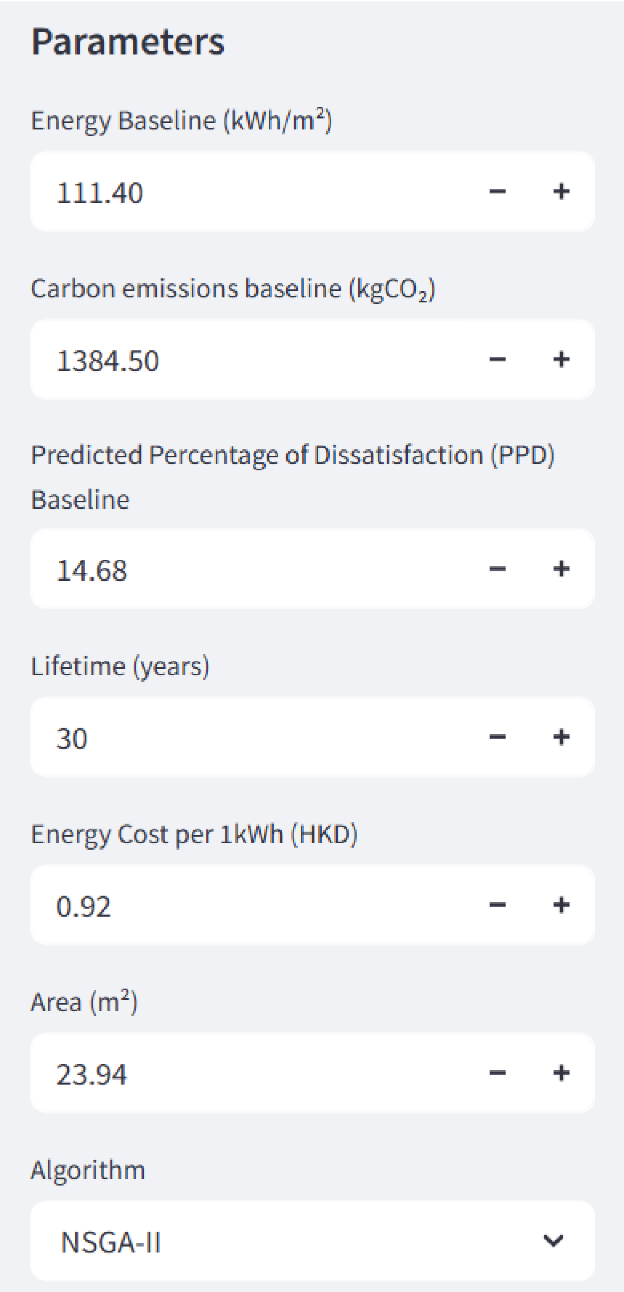


Figure 9.6: Sidebar to include the parameters of the existing building and to select the algorithm.

The system incorporates a file upload functionality to facilitate the input of data pertaining to retrofit strategies (Figure 9.7). This feature enables users to upload a dataset in either CSV or Excel file format, encompassing information on post-retrofit energy consumption, carbon emissions, and PPD, along with the initial costs and the embodied carbon associated with the retrofit strategies employed in the context of building NZC retrofitting. Upon completion of the data input, the interface prompts users to engage with a distinct section labeled "configuration", where they are tasked with selecting variables for optimization (select decision variables) and aligning the columns of the model with their corresponding counterparts in the uploaded dataset (map target columns) to ensure coordination with the model's requirements. Throughout the data upload process within the decision-making model, users are presented with the option to either proceed with the provided sample dataset or upload their own structured data file. This aspect of the model allows it to adapt to various decision-making needs and practices.

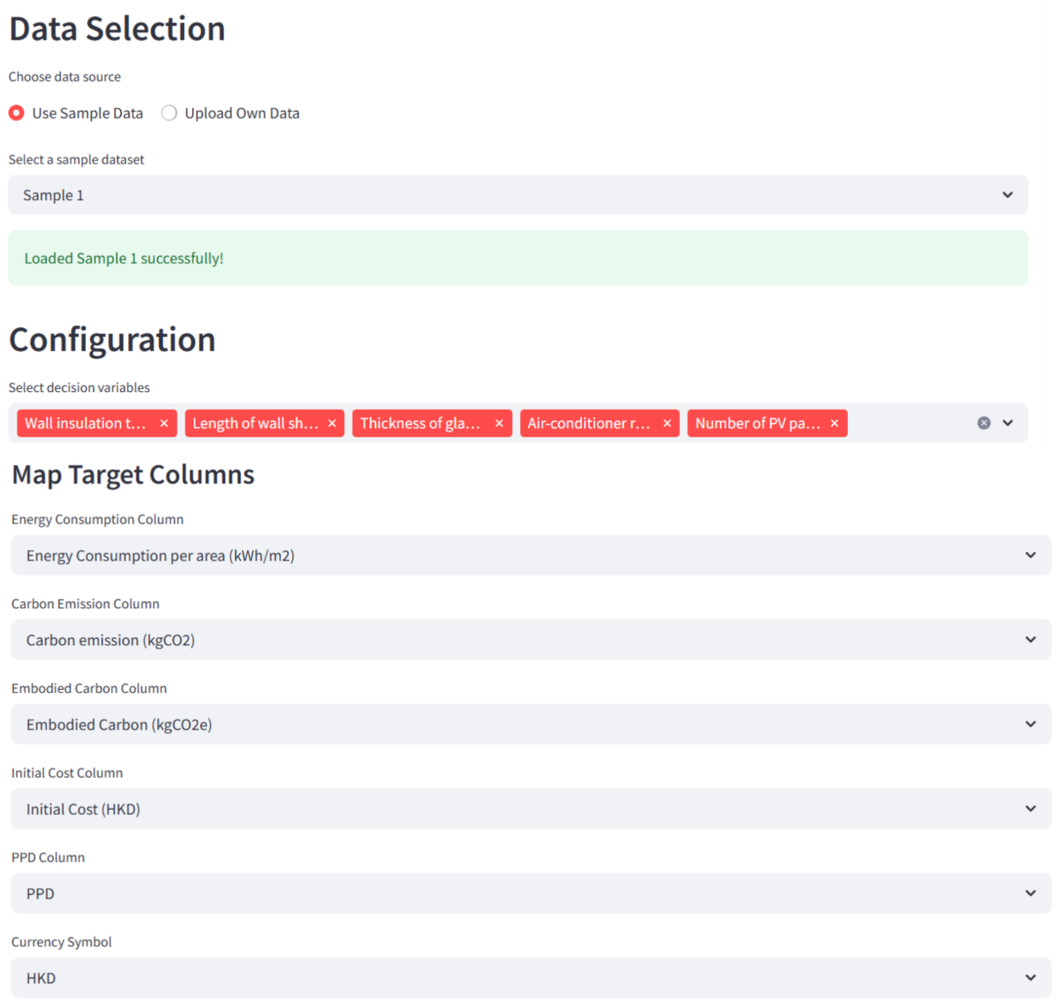


Figure 9.7: User interface for data selection and configuration.

9.4.2 Outputs from the Model

Upon the completion of the data input, the model transitions to the data analysis segment (Figure 9.8). Subsequently, the user interface shows information pertaining to the decision variables essential for optimization, alongside a preview of the processed data derived from the uploaded file designated for optimization. This functionality not only contributes to the visual appeal of the model but also ensures the availability of decision variable options for users. To obtain the model output, users are prompted to initiate the optimization process by clicking "Start Optimization".

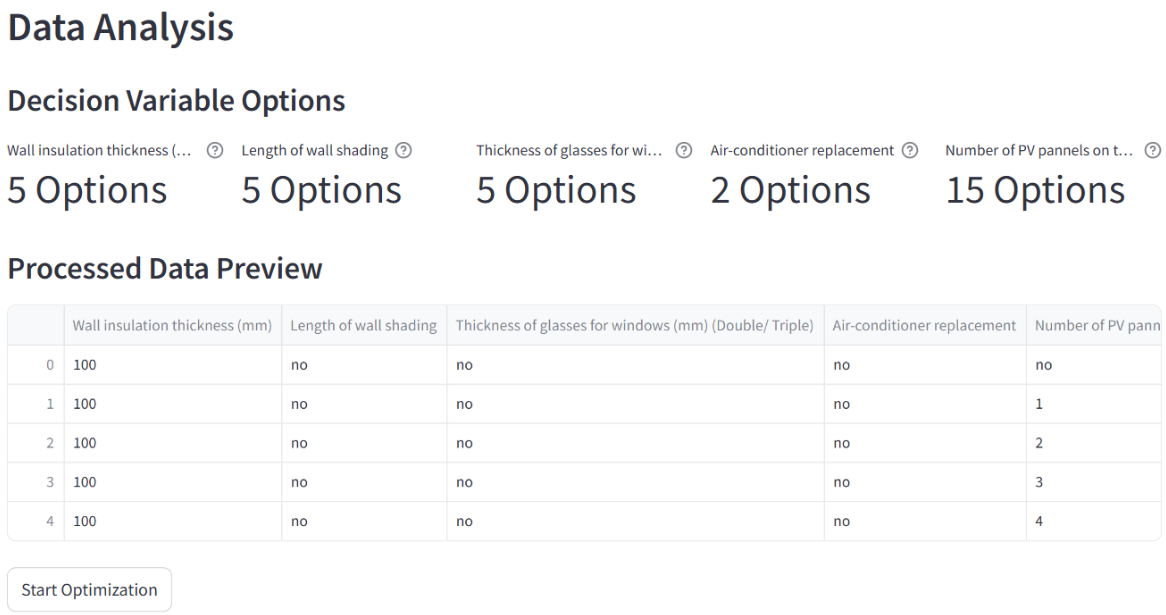


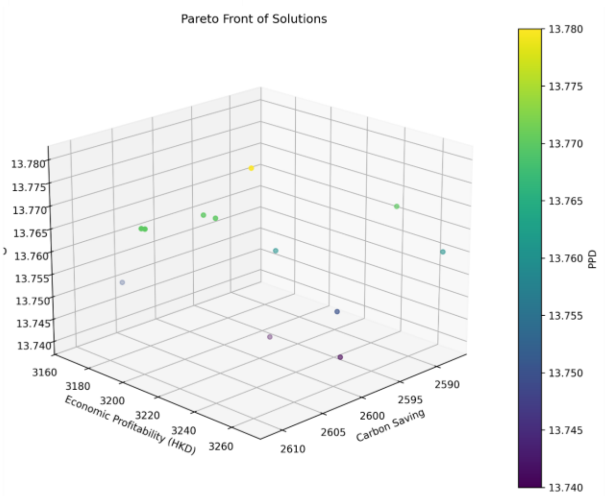
Figure 9.8: User interface displaying the details of analyzed data from the selected dataset.

Following the optimization procedure, the outcomes are presented in the lower section of the interface, exhibiting a Pareto front illustrating optimized solutions and two-dimensional plots showcasing solutions with the objectives of the optimization (space analysis of solutions) (Figure 9.9). The optimization results are presented in a tabular format, encompassing details concerning carbon savings, economic profitability, and PPD. Users can conveniently review these optimization solutions directly within the interface. Moreover, users retain the option to download the results in CSV and PNG formats for further analysis and recording. This attribute proves especially beneficial for decision-makers engaged in extensive evaluations concerning building NZC retrofitting endeavors.

Optimization Results

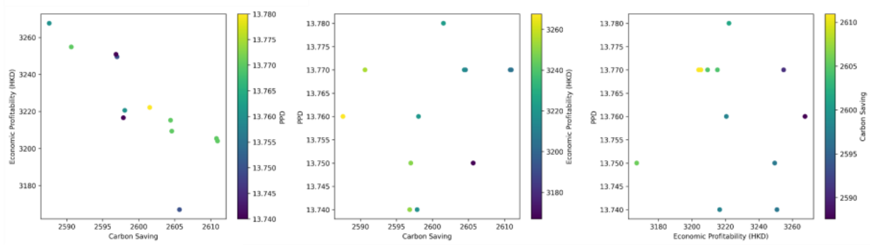
	Wall insulation thickness (mm)	Length of wall shading	Thickness of glasses for windows (mm) (Double/ Tripl
27	75	400	6,6,6
33	100	400	6,6,6
6	100	400	4,4,4
17	50	400	6,6,6
37	75	400	6,6
7	25	400	6,6,6
16	50	400	6,6
25	100	400	6,6
81	75	400	4,4
79	100	400	4,4
49	50	400	4,4
3	25	400	4,4

Pareto Front



Download Pareto Front Plot

Solution Space Analysis



Download Solution Space Plot

Download Results CSV

Figure 9.9: Interface representing the output from the model (optimization results).

9.5 Chapter Summary, Contributions, and Limitations

Building NZC retrofitting is a timely solution to achieve the targets set in the Paris Agreement, as well as to create a zero-emission built environment. With the availability of numerous retrofit measures, decision-makers are struggling to select optimized retrofit strategies that align with sustainable features. While existing studies predominantly center on energy efficiency and cost considerations within the realm of environmental and economic sustainability, there exists a notable gap in the literature regarding the comprehensive evaluation of carbon emissions, occupant satisfaction, and economic profitability, emphasizing the triple bottom line of sustainability. Therefore, this chapter attempted to address this gap by developing a model to make optimized decisions on building NZC retrofitting concerning carbon saving, occupant satisfaction, and economic profitability, thereby focusing triple bottom line of sustainability. Hence, this chapter developed two optimization models concerning annual and lifetime performances of retrofit strategies following building NZC retrofitting.

Accordingly, the optimization model was developed by defining objectives and constraints focusing on the social, environmental, and economic sustainability, and different retrofit measures were identified as the decision variables of the model. Three algorithms, NSGA II, NSGA III, and AGE-MOEA were employed to assess the reliability and the robustness of the model. The data collected through the case study in Chapters 7 and 8 were used for implementation and the validation of the model. Finally, the optimization models were incorporated into the Streamlit framework for the deployment of the model as a web application.

The application of the optimization model yielded a set of 12 optimal solutions tailored toward achieving NZC residential buildings in Hong Kong. These solutions were characterized by their emphasis on maximizing carbon savings, maximizing economic profitability, and minimizing occupant dissatisfaction. The optimized retrofit strategies encompassed strategies, including variations in wall insulation thickness (ranging from 25mm to 100mm), options for retrofitting windows with double or triple-glazed panes (4mm and 6mm thick) featuring PVC frames, the incorporation of 400mm external wall shading, and installations of 14 PV panels. Despite the robustness of the optimization model, the uniformity in the optimized solutions derived from the model concerning both annual and lifetime performances can be attributed to constraints tied to data collection limitations.

The outcomes derived from this chapter hold substantial significance in informing sustainable policymaking endeavors and subsequent investment initiatives concerning the retrofitting of residential buildings to NZC within Hong Kong. Furthermore, the deployment of the developed web application tailored for optimized decision-making stands to offer invaluable support to decision-makers and various stakeholders operating within the realm of building NZC retrofitting, including building occupants. This model facilitates the precise evaluation of NZC retrofitting options with a keen focus on occupant satisfaction, carbon reduction potentials, and economic profitability. Moreover, the research findings presented in this chapter serve as a foundational resource for researchers aiming to define objectives, constraints, and variables essential for conducting multi-objective optimization within the context of building NZC retrofitting. The insights gathered from the optimization models can be leveraged by researchers to determine optimal retrofit strategies applicable to corresponding subtropical regions striving to achieve NZC from the existing residential buildings.

While this chapter presents notable contributions to both academia and industry practitioners, it is essential to acknowledge several inherent limitations. The methodology employed for quantifying carbon saving and economic profitability relied on data derived from annual carbon emissions and energy consumption, a factor common to both models concerning the annual and lifetime performances following NZC retrofitting. It is therefore suggested that forthcoming researchers undertake distinct simulations spanning the lifetime of the building to gauge the energy consumption and carbon emissions arising during post-NZC retrofitting. Furthermore, the optimization model's scope was confined to the NSGA II, NSGA III, and AGE-MOEA algorithms, underscoring the necessity of incorporating additional multi-objective optimization algorithms to compare the reliability and robustness of the model. Further, the optimal solutions were provided focusing on the residential buildings in Hong Kong, thereby limiting the generalizability of the findings. Despite these limitations, the findings of this chapter have significant implications for both academia and industry practitioners, providing vital insights to guide informed and sustainable decision-making processes in the field of building NZC retrofitting.

CHAPTER TEN

10.0 Conclusions and Recommendations

10.1Introduction

Chapters 1-9 encompass different aspects of this study. The introduction to the study provided in Chapter 1, followed by methodologies to achieve objectives outlined in Chapter 2, existing literature relevant to the study's objectives explored in Chapter 3, and empirical findings aligned with the study's objectives described in Chapters 4-9. The current chapter serves as the conclusion to this research study, revisiting the research objectives and delivering major conclusions. Additionally, it explains the theoretical and practical implications of the study. Lastly, this chapter discusses the study's limitations and provides recommendations for future research studies.

10.2Review of Research Objectives and Conclusions

This research study aimed to develop a model to select the optimal retrofit strategy for maximizing social, environmental, and economic sustainability in residential building NZC retrofitting. Accordingly, the following objectives were established to achieve the aim of the study.

1. To analyze and model the challenges and benefits of retrofitting existing residential buildings for NZC.
2. To identify and model the available retrofitting measures to reduce carbon emissions in existing residential buildings.
3. To evaluate the social, environmental, and economic sustainability changes due to retrofitting.

4. To develop a model to select optimal retrofit strategies for NZC retrofitting of existing residential buildings.

Numerous research methods were employed in this study (Chapter 2) to accomplish the objectives. Chapters 4-9 described the main findings and conclusions for each objective. A summary of those chapters is provided below by reviewing each objective.

Objective 1: To analyze and model the challenges and benefits of retrofitting existing residential buildings for NZC (Chapters 4 and 5).

A comprehensive literature review was conducted through published literature sources to identify the benefits and challenges of retrofitting existing residential buildings for NZC. Accordingly, 17 benefits and 28 challenges were revealed from the comprehensive literature review. The benefits were identified under three groups: social benefits, environmental benefits, and economic benefits, while the challenges were identified under six groups: social challenges, financial challenges, industrial and stakeholder challenges, administrative challenges, technical challenges, and geographical challenges. The agreement of building occupants with the influence of identified challenges and benefits for the residential building NZC retrofitting was assessed through a questionnaire survey within Hong Kong. The results indicated that 17 benefits (Chapter 4) and 28 challenges (Chapter 5) significantly influenced the residential building NZC retrofitting.

The top three benefits that greatly motivate the residential building NZC retrofitting were identified as: (1) "lower building maintenance costs", (2) "reduce energy costs", and (3) "attractive return on investments" (Chapter 4). PLS-SEM was employed to analyze and model the influence of benefits on the residential building NZC retrofitting. The analysis highlighted the significant influence of "economic benefits" and "environmental benefits" on residential building NZC retrofitting. Even though "social benefits" did not significantly influence residential building NZC retrofitting, they were the driving force behind the generation of "economic benefits" (Chapter 4).

The top three critical challenges for residential building NZC retrofitting were identified as: "obstacles to domestic renewable energy (i.e., technical limitations, climate variations, and regulatory issues)", "difficulties due to high-rise, high-density urban environments", and "lack of knowledge and awareness on retrofitting". PLS-SEM was implemented to analyze and model the relationship between challenges and residential building NZC retrofitting. Results indicated that "social challenges" and "technical challenges" had a significant impact on residential building NZC retrofitting. In addition, "geographical challenges" were identified as a driving force behind the emergence of "technical challenges", while "administrative challenges" and "industrial and stakeholder challenges" were the driving forces behind the emergence of "social challenges". Even though "financial challenges" did not significantly influence residential building NZC, they had a significant influence on "administrative challenges", which were identified as a driving force to "social challenges" (Chapter 5).

The findings of the analysis, as well as the PLS-SEM model of benefits and challenges, would be extremely valuable to researchers, industry practitioners, policymakers, and advocates looking for empirical quantitative proof and clarification about the influences of benefits and challenges on the residential building NZC retrofitting. Hence, the outcomes and models from this research objective can assist researchers, policymakers, industry practitioners, and advocates in promoting NZC retrofitting in existing residential buildings with the aim of creating a zero-emission built environment.

Objective 2: To identify and model the available retrofitting measures to reduce carbon emissions in existing residential buildings (Chapter 6).

Forty-three potential retrofitting measures under three categories: (1) building envelope upgrades, (2) energy system upgrades, and (3) renewable energy upgrades, were identified through the comprehensive literature review. Building occupant's preferences towards different categories of retrofit measures were assessed through a questionnaire survey among building occupants within Hong Kong. In addition, a separate questionnaire survey was conducted among experts in the domain of building NZC retrofitting within Hong Kong to assess the importance of identified retrofit measures.

The Friedman test was utilized to assess the preferences of building occupants toward different retrofit categories. Results highlighted that building occupants mostly preferred renewable energy upgrades rather than building envelopes and energy system upgrades. In addition, the use of solar energy, retrofitting lighting system, and wall retrofitting stood as the most preferred measures among renewable energy upgrades, energy system upgrades, and building envelope upgrades, respectively.

The results of the survey with experts indicated that all the measures have significant potential to convert existing residential buildings within Hong Kong to NZC. PLS-SEM was employed to assess the appropriateness of different retrofitting measures for the residential building NZC within Hong Kong. Results of the PLS-SEM demonstrated that wall and window retrofitting measures were most suitable among building envelope upgrades, while HVAC system and hot water system retrofitting were the most suitable for upgrading the energy systems of residential buildings in Hong Kong to achieve NZC. Furthermore, results indicated that the integration of solar energy sources played a significant role in the attainment of NZC residential buildings from existing buildings in the context of Hong Kong.

The findings from the two questionnaire surveys, as well as the PLS-SEM model of retrofit measures, would be extremely valuable to researchers, industry practitioners, policymakers, and advocates looking for empirical quantitative proof and clarification about the suitability of retrofit measures to achieve NZC residential buildings within Hong Kong. Accordingly, the outcomes and models from this research objective can assist researchers, policymakers, industry practitioners, and advocates in promoting NZC retrofitting in existing residential buildings with the aim of creating a zero-emission built environment.

Objective 3: To evaluate the social, environmental, and economic sustainability changes due to retrofitting (Chapters 7 and 8).

The comprehensive literature review revealed that the amount of carbon-saving, economic profitability, and PPD can be used to evaluate the environmental, economic, and social sustainability following the residential building NZC retrofitting, respectively. Accordingly, a case study was conducted to assess social, environmental, and economic sustainability due to NZC retrofitting. Retrofit measures to develop strategies were selected based on the findings from the Friedman test and PLS-SEM. Accordingly, 3735 retrofit strategies were formulated by incorporating different parameters of wall insulation (25mm, 50mm, 75mm, 100mm), wall shading (100mm, 200mm, 300mm, 400mm), double and triple glazed windows with PVC frame (4mm and 6mm thick), replacement of air conditioner, and implementation of PV panels.

Two-person unit within a residential building in Hong Kong was selected as the case study to assess the sustainability features following NZC retrofitting. The IESVE software was used as a simulation tool to assess carbon emissions, energy consumption, and PPD with the implementation of retrofit strategies. OneClick LCA was employed to assess the embodied carbon of retrofit materials, and a market survey was conducted to evaluate the costs of retrofit materials. Finally, the results from the simulations, embodied carbon calculations, and market survey were used to conduct social, environmental, and economic sustainability analysis following the NZC retrofitting using the developed retrofit strategies.

The results indicated that 3735 retrofit measures perform carbon savings, positive economic profits, and lower PPD values compared with the base case, representing environmental, economic, and social sustainable features following the NZC retrofitting. Further, the results highlighted that the highest social, environmental, and economic sustainable performances were achieved by different retrofit strategies, showing that the results were not consistent with different aspects of sustainability. These sustainable performances related to different retrofit strategies would be valuable for researchers, as well as decision-makers in the domain of NZC retrofitting, to quantitatively represent the sustainable features following the residential building NZC retrofitting. Therefore, the findings from this research objective can assist researchers, policymakers, decision-makers, and advocates in promoting sustainable NZC retrofitting in existing residential buildings with the aim of creating a zero-emission built environment.

Objective 4: To develop a model to select optimal retrofit strategies for NZC retrofitting of existing residential buildings (Chapter 9).

The comprehensive literature review revealed different optimization algorithms to solve multi-objective problems. Accordingly, NSGA II, NSGA III, and AGE-MOEA were employed to conduct multi-objective optimization to decide optimal retrofit strategies with maximized carbon saving, maximized economic profitability, and minimized occupant dissatisfaction. Accordingly, a multi-objective optimization model was developed employing three different algorithms to assess the reliability and robustness of the model. However, two models were developed that focused on the annual and lifetime performance of the building following NZC retrofitting. The models' objectives, constraints, and variables were defined focusing on sustainable concepts and retrofit measures. The case study's data on post-retrofit energy consumption, carbon emission, and PPD, along with embodied carbon and initial costs of the retrofit strategies (Chapter 8), were used to implement and validate the optimization models. The results demonstrated twelve optimal solutions to achieve NZC residential buildings within Hong Kong. Further, the similar outcomes from three different algorithms represented the reliability and robustness of the optimization models.

Finally, the optimization models were incorporated into the Streamlit framework. Accordingly, a web application was developed within the Streamlit framework using Python and its relevant libraries for backend functionality and HTML and CSS for frontend designs. As a result, a web application with a user-friendly interface was developed to make optimal decisions on building NZC retrofitting, focusing on social, environmental, and economic sustainability. The web application was further validated through the two different datasets developed from the case study. Hence, this web application would be of great value for decision-makers to decide the optimal retrofit strategies for NZC retrofitting while achieving social, environmental, and economic sustainability. Therefore, the outcomes of this research objective can assist decision-makers in achieving NZC buildings while enhancing social, environmental, and economic sustainability.

10.3Novelty and Contributions of the Study

Chapters 4-9 have extensively examined the research findings, revealing the novelty, significance, and contributions of this study in alignment with its predefined objectives. To avoid unnecessary repetition, this section concisely summarizes the novelty and contributions of the research.

Numerous studies have focused on building retrofitting to reduce energy consumption and carbon emissions. Despite these efforts, the construction industry continues to face the enormous issue of lowering carbon emissions caused by existing buildings. Therefore, this study examined NZC retrofitting existing residential buildings. As a result, this study investigated the challenges and benefits of residential building NZC retrofitting, measures that can be used to retrofit the existing residential buildings to NZC, and the selection of optimal retrofit strategies to achieve NZC residential buildings, enhancing the social, environmental, and economic sustainability. So, this study followed varied methodological approaches in order to address the identified knowledge gaps discovered by a comprehensive literature review. Consequently, the study analyzed and modeled the relationships between challenges and residential building NZC retrofitting, benefits and residential building NZC retrofitting, and measures and residential building NZC retrofitting, to close the gaps identified based on the analysis of challenges, benefits, and measures. Further, the study evaluated the sustainability of identified retrofit measures through a case study and conducted an optimization to decide optimal strategies to achieve NZC residential buildings in Hong Kong while enhancing social, environmental, and economic sustainability. Using the models developed for optimization, a web tool was created to facilitate an optimal decision-making process in building NZC retrofitting, which is essential for the domain of NZC retrofitting.

Based on the findings from Chapters 4 to 9, this study makes significant contributions to existing literature. The assessment of challenges, benefits, and measures of residential building NZC retrofitting through the mean score ranking method provides a systematic way to promote the most influential challenges, benefits, and measures. Further, the model created for benefits and challenges based on the building occupant's opinions serves as a useful reference for future research studies in similar areas. In addition, the model created for retrofit measures using the inputs from experts in the domain of NZC retrofitting serves as a reference to determine the suitable retrofit measures for future studies. The findings from sustainability analysis and optimization potentially help and motivate future research to develop further strategies to achieve NZC residential buildings. The developed optimization model acts as a roadmap for future researchers to encourage building NZC retrofitting while enhancing sustainable features.

As discussed in Chapters 4-9, the findings from this research have significant contributions to industry practitioners, policymakers as well as advocates, especially focusing on the residential buildings in developed regions. The identification and ranking of benefits and challenges offer actionable guidance for policymakers, retrofitting companies, and facility managers. Further, this study identified significant challenges for residential building NZC retrofitting and represented the relationship between them, showing that they are not influenced independently. This would assist stakeholders in identifying limitations and developing strategies to promote residential building NZC retrofitting. Similarly, the benefits model would support enhancing policy actions in order to improve and promote the residential building NZC retrofitting. Accordingly, two models suggest the way to develop promotional strategies to promote NZC retrofitting. Hence, these models contribute directly to Hong Kong’s carbon neutrality objectives by elucidating pathways to accelerate the adoption of residential building retrofitting. In addition, the identified optimal retrofit strategies can be implemented in residential units to achieve NZC in Hong Kong. The evaluation of retrofit measures based on the opinions of building occupants and experts provides guidelines for industry practitioners in developing retrofit strategies to achieve NZC residential buildings. The sustainable assessment of retrofit strategies and optimization provides guidelines for decision-makers and other stakeholders to decide the optimal retrofit strategies to achieve NZC residential buildings, specifically focusing on Hong Kong and other developed regions with similar climate characteristics. Further, the web application developed through this study supports decision-makers in deciding optimal retrofit strategies to achieve NZC buildings.

Accordingly, the findings of each research objective provide essential theoretical and practical contributions to residential building NZC retrofitting within Hong Kong and other developed regions across the world. Finally, this study makes significant contributions to creating a sustainable and zero-emission built environment.

10.4 Limitations of the Study

Even though this study has significant contributions while achieving the research aim and objectives, the study is subject to several limitations that should be acknowledged. First, this study was limited to NZC retrofitting of residential buildings in Hong Kong. As a result, there might be limitations in the generalization of the results. Second, due to the novelty of building NZC retrofitting in Hong Kong, the questionnaire survey evaluations of this study were based on relatively small samples of building occupants and experts with an awareness of building NZC retrofitting. Hence, the evaluations and assessments made in this study were generally subjective and might have been impacted by respondents' experiences and opinions. Third, the optimization was limited to data collected from a two-person unit within a residential building in Hong Kong due to the difficulties in collecting data from different residents within the entire building. Further, there are limitations specific to research objectives as presented under the section "chapter summary, contributions, and limitations" of chapters 4 - 9.

10.5 Recommendations for Future Research

While the current study has examined and evaluated the issues that are critical to promoting residential building NZC retrofitting, there are still opportunities for future research in this domain.

First, this study was focused on the residential building NZC retrofitting. However, other building types, including industrial, commercial, health, and educational, need to be considered to achieve NZC from the existing building stock.

Second, the benefits and challenges were analyzed based on the 123 responses from Hong Kong building occupants, while the measures were analyzed based on 52 responses from Hong Kong domain experts. Future studies must focus on larger responses. In addition, the incorporation of opinions from numerous stakeholders, including facility managers, project managers, decision-makers, and government organizations, to evaluate the challenges and benefits of residential building NZC retrofitting may provide further information on the deviation of stakeholder’s perspectives on the challenges and benefits. Further, this study can be extended to other developed as well as developing regions.

Third, this study followed a simulation method to calculate carbon emissions from the base case. So, future studies may incorporate sensors or any other equipment to directly measure the carbon emissions from the base case.

Fourth, although the study developed a web application to determine the optimal retrofit strategies, the data related to the retrofit strategies needs to be input into the model manually. So, future studies may incorporate digital twin and other technologies to digitalize the decision-making in building NZC retrofitting.

Finally, while the findings and contributions of this research might offer value to policymakers and professionals in other developed regions, given the study’s concentration on the developed region of Hong Kong, forthcoming research studies could target other developed as well as developing regions. This could play a pivotal role in formulating insights, models, and optimal retrofit strategies conducive to efficient and effective NZC retrofitting in distinct regional contexts. Such a holistic approach is imperative, considering the inherently contextual nature of sustainability within the domain of the built environment (Jarrar & Al-Zoabi, 2008). Owing to the variances in climatic settings and architectural typologies across diverse regions, the pursuit of NZC building retrofitting gas necessitated the adoption of regional-specific retrofit strategies.

The other recommendations for future research specific to the research objectives are described within the section “chapter summary, contributions, and limitations” in Chapters 4-9.

10.6Chapter Summary

This chapter concludes with the current research study. Accordingly, the chapter described the major conclusions from the research objectives. Further, the research's novelty and contributions have been highlighted, along with recommendations for future research studies. Hence, this chapter closed the current research study. The appendices and the references to the study are presented on the following pages.

APPENDIX A

QUESTIONNAIRE FOR BUILDING OCCUPANTS

To whom it may concern

Dear Sir/ Madam,

Invitation to Participate in a PhD Research on "Development of a Model for Sustainable Decision-making in Net Zero Carbon Retrofitting of Existing Residential Buildings"

I am a full-time PhD research student in the Department of Building and Real Estate at The Hong Kong Polytechnic University. My research focuses on proposing a method to make optimal decisions concerning social, environmental, and economic sustainability in retrofitting existing residential buildings to convert them into net zero carbon (NZC) buildings as a solution to the adverse climatic effects. Hence, this research aims to develop a model to decide the optimal retrofit strategy concerning social, environmental, and economic sustainability in residential building NZC retrofitting. The research is being carried out under the supervision of Dr. Amos Darko and Prof. Albert P.C. Chan.

As part of my data collection process for this research, I am conducting a questionnaire survey among residential building occupants to identify the benefits, challenges, and measures for NZC retrofitting. You are cordially invited to participate in this questionnaire survey (Ethical approval Ref No HSEARS20231101003). The confidentiality of all participants will be maintained throughout the whole research study and your identities will not be revealed in any documents or events related to this study. I hereby certify that the information collected will solely be used for academic purposes.

I understand that this questionnaire survey will consume your precious time. However, this research will not be successful without your valuable participation. I would be grateful if you could respond to the questionnaire within two weeks. I believe that the overall research findings will significantly contribute to establishing a well-developed model for sustainable decision-making in retrofitting existing residential buildings towards NZC.

Thank you for your invaluable time. If you have any questions, please email Lichini Nikesha at lichininikesha.weerasinghe@.

Yours faithfully,

Lichini Nikesha,
PhD Research Student
Department of Building and Real Estate, The Hong Kong Polytechnic University,
Email: lichininikesha.weerasinghe@
Tele: +852 5446

Questionnaire Survey

Section 1: Definitions of key terms

1. Retrofitting: Making alternations to the existing building to reduce energy consumption and carbon emissions.
2. Net zero carbon (NZC): Reducing the annual carbon emissions of the building associated with the operational energy to zero or negative.

Section 2: Background information of the respondent

1. What is your relationship with the current building that you live in?

   - Owner ☐
   - Tenant ☐

2. How long have you lived in Hong Kong?

   - Between 0 - 1 year ☐
   - Between 2- 3 years ☐
   - Between 4-5 years ☐
   - More than 5 years ☐

3. What is the age of the building that you lived in?

   - Between 0-10 years ☐
   - Between 11-20 years ☐
   - Between 21-30 years ☐
   - Between 31-40 years ☐
   - More than 40 years ☐
   - Don't know ☐

4. Are you aware of building retrofitting/renovation to achieve Net Zero Carbon (NZC) buildings?

   - not aware at all ☐
   - slightly aware ☐
   - somewhat aware ☐
   - Moderately aware ☐
   - Extremely aware ☐

Section 3: Retrofitting measures to convert existing residential buildings into NZC buildings.

1. Kindly number the following types of retrofitting measures according to your preference. (Give 1 for the highly preferred measure)

   - Building envelope/ component upgrades (floor, wall, roof, etc.) [ ]
   - Energy system upgrades (lighting systems, hot water systems, etc.) [ ]
   - Renewable/ reusable energy upgrades (solar and wind energy) [ ]

2. Kindly number the following retrofitting measures under the building envelope/components according to your preference. (Give 1 for the highly preferred measure)

   - Roof retrofitting [ ]
   - Wall retrofitting [ ]
   - Window retrofitting [ ]
   - Door retrofitting [ ]
   - Floor retrofitting [ ]

3. Kindly number the following retrofitting measures under the energy systems according to your preference. (Give 1 for the highly preferred measure)

- HVAC system retrofitting ☐
- Hot water system retrofitting ☐
- Lighting system retrofitting ☐
- Replacement of appliances ☐

4. Kindly number the following retrofitting measures under renewable energy according to your preference. (Give 1 for the highly preferred measure)
   - Solar energy ☐
   - Wind energy ☐

Section 4: Benefits of retrofitting existing residential buildings to convert them into NZC buildings.

Kindly rate the degree of agreement with the following benefits of retrofitting existing residential buildings towards NZC buildings.

1 – strongly disagree
2 – disagree
3 – neutral
4 – agree
5 – strongly agree

Benefits of retrofitting existing residential buildings towards NZC buildings	**Degree of agreement**				
	1	**2**	**3**	**4**	**5**
Social benefits					
Improve building comfort (thermal, natural, lighting, acoustic, etc.)					
Enhance the quality of life for occupants					
Increase efficiency and reliability of the building systems					
Provide better building appearance/ aesthetics					
Increase building usable time					
Increase indoor and outdoor environmental quality					
Create new job opportunities					
If there are any social benefits, please list and rate them					
Environmental benefits					
Reduce environmental pollution					
Reduce energy consumption and secure energy supply					
Reduce carbon and GHG emissions					
Minimize adverse climatic effects					
If there are any environmental benefits, please list and rate them					
Economic benefits					
Increase the building value					
Reduce energy costs					
Increase accessibility to incentives and subsidies					
Lower building maintenance costs					
Attractive return on investments					
Reduce vulnerability to fluctuating prices					
If there are any benefits, please list and rate them					

Section 5: Challenges for retrofitting existing residential buildings to convert them into NZC buildings.

Kindly rate the degree of agreement with the following challenges for retrofitting existing residential buildings towards NZC buildings.

1 – strongly disagree
2 – disagree
3 – neutral
4 – agree
5 – strongly agree

Challenges for retrofitting existing residential buildings towards NZC buildings	**Degree of agreement**				
	1	**2**	**3**	**4**	**5**
Social and cultural challenges					
Reluctance to change attitudes					
Doubts regarding energy savings and reduction of carbon emission					
Unwilling to invest in a retrofit					
Lack of knowledge and awareness on retrofitting (i.e., measures, benefits, and market)					
If there are any challenges, please list and rate them					
Financial challenges					
Uncertainty about payback time or return on investment					
High initial cost					
Complicated to access the financial data					
Lack of incentives and financial support					
If there are any challenges, please list and rate them					
Industrial and Stakeholder challenges					
Lack of reliability of the stakeholders who execute the work					
Uncertainty about the available technologies					
Lack of collaboration among stakeholders					
Lack of professional knowledge and skills					
Poor understanding of sustainability and Net Zero targets					
Fragmentation of the supply chain					
Lack of promotion platforms					
If there are any challenges, please list and rate them					
Administrative challenges					
Lack of support from the government					
Complex permit procedures					
Unavailability of standardized approaches to prevent climatic variations					
Lack of coordination mechanism					
Lack of continuity, consistency, and flexibility of retrofit policies					
Lack of effective strategic programs					

Conflict with other building codes and regulations					
If there are any challenges, please list and rate them					
Technical challenges					
Complexity of the existing residential buildings					
Lack of data and information about building systems					
Lack of widespread adoption of energy efficiency, renewable, and smart technologies.					
If there are any challenges, please list and rate them					
Geographical challenges					
Variation in the climatic conditions					
Difficulties due to high-rise, high-density urban environment					
Obstacles to domestic renewable energy (i.e., technical limitations and regulatory issues)					
If there are any challenges, please list and rate them					

Section 6: Building retrofitting methods.

Kindly rate the degree of agreement with the following building retrofitting methods to convert existing residential buildings to NZC.

1 – strongly disagree
2 – disagree
3 – neutral
4 – agree
5 – strongly agree

Methods of building retrofitting	**Degree of agreement**				
	1	**2**	**3**	**4**	**5**
Building envelope upgrades					
Energy system upgrades					
Renewable energy upgrades					

Note: If you would like to receive a summary of the research findings, kindly provide your NAME and the EMAIL ADDRESS.

Name: ………………………….   Email: ………………………………

The End

Thank you for your generous participation!!!

Kind request: You may also forward this survey questionnaire to other colleagues or platforms that could contribute to the success of this research.

APPENDIX B

QUESTIONNAIRE FOR EXPERTS

To whom it may concern

Dear Sir/ Madam,

<u>Invitation to Participate in a PhD Research on "Development of a Model for Sustainable Decision-making in Net Zero Carbon Retrofitting of Existing Residential Buildings"</u>

I am a full-time PhD research student in the Department of Building and Real Estate at The Hong Kong Polytechnic University. My research focuses on proposing a method to make optimal decisions concerning social, environmental, and economic sustainability in retrofitting existing residential buildings to convert them into net zero carbon (NZC) buildings as a solution to the adverse climatic effects. Hence, this research aims to develop a model to decide the optimal retrofit strategy concerning social, environmental, and economic sustainability in residential building NZC retrofitting. The research is being carried out under the supervision of Dr. Amos Darko and Prof. Albert P.C. Chan.

As part of my data collection process for this research, I am conducting a questionnaire survey among experts in the domain of NZC retrofitting to identify the measures for residential building NZC retrofitting. You are cordially invited to participate in this questionnaire survey (Ethical approval Ref No HSEARS20231101003). The confidentiality of all participants will be maintained throughout the whole research study and your identities will not be revealed in any documents or events related to this study. I hereby certify that the information collected will solely be used for academic purposes.

I understand that this questionnaire survey will consume your precious time. However, this research will not be successful without your valuable participation. I would be grateful if you could respond to the questionnaire within two weeks. I believe that the overall research findings will significantly contribute to establishing a well-developed model for sustainable decision-making in retrofitting existing residential buildings towards NZC.

Thank you for your invaluable time. If you have any questions, please email Lichini Nikesha at lichininikesha.weerasinghe@.

Yours faithfully,

Lichini Nikesha,
PhD Research Student
Department of Building and Real Estate, The Hong Kong Polytechnic University,
Email: lichininikesha.weerasinghe@
Tele: +852 5446

Questionnaire Survey

Section 1: Background information of the respondent

5. What is your profession?
   - Engineer ☐
   - Architect ☐
   - Project Manager ☐
   - Consultant ☐
   - Others, please specify: ………………
6. What are your years of working experience in the construction industry?
   - 1-5 years ☐
   - 6-10 years ☐
   - 11-15 years ☐
   - 16-20 years ☐
   - Over 20 years ☐
7. Are you aware of building retrofitting/renovation to achieve Net Zero Carbon (NZC) buildings?
   - Not aware at all ☐
   - slightly aware ☐
   - somewhat aware ☐
   - Moderately aware ☐
   - Extremely aware ☐

Section 2: Retrofitting measures to convert existing residential buildings into NZC buildings.

Please indicate the level of importance of each of the following retrofitting measures to convert existing residential buildings into NZC buildings. Use the following scale.

1 – not important
2 – less important
3 – neutral
4 – important
5 – very important

Building envelope upgrades

Retrofitting measures	Level of importance				
	1	2	3	4	5
Roof retrofitting					
Ceiling insulation					
Implementation of roof plastering with low solar absorptance					
Apply a layer of black high-density polyethylene (HDPE) net with 90% shading as a roof cover					
Apply vegetation					

Add insulation					
Apply cement tile or light-colored linoleum-pressed steel sheet					
If there are any measures, please list and rate them					
Wall retrofitting					
Add insulations					
Apply shadings					
Green facade					
Apply thermal plasters					
Facade insulations					
Aerogel plaster on the external wall					
Adding vapor barriers to the facade					
If there are any measures, please list and rate them					
Window retrofitting					
Install triple-glazed widows					
Use of energy-efficient glazing (low e values)					
Sealings of windows and joint places					
Install double-glazed windows					
Adjust window to wall ratio					
Install automatic shading devices above the windows					
Apply thin film coating on the windows					
Fill argon gas between two layers of glass					
Use PVC window frame with double glazing					
Use polyvinylchloride PVC window frame with triple glazing					
Dynamic window replacement module, which includes automated solar-tracking blinds for shading control with night insulation properties					
Replace windows with low U-value windows					
If there are any measures, please list and rate them					
Door retrofitting					
Replace with new energy-efficient doors					
Use double-glazed doors					
Upgrade double-glazed PVC units with air-filled gaps					
If there are any measures, please list and rate them					
Floor retrofitting					
Add insulation					
Upgrade floor finishes and coverings					
If there are any measures, please list and rate them					

Energy system upgrades

Retrofitting measures	Level of importance				
	1	2	3	4	5
HVAC system					
Apply new central heating systems					
Use of efficient heat pumps					
Update the entire HVAC system					
Adjust the heating and cooling set point in an efficient way					
Use a ventilation system with heat recovery ventilation					
Use high-efficiency boilers and cooling sources					
If there are any measures, please list and rate them					
Hot water system					
Use an electric water heater					
Install a domestic hot water system					
If there are any measures, please list and rate them					
Lighting system					
Control the lighting level and equipment operation					
Improve natural ventilation and lighting					
Replacement of light bulbs with efficient bulbs					
If there are any measures, please list and rate them					

Renewable energy upgrades

Retrofitting measures	Level of importance				
	1	2	3	4	5
Solar energy					
Install solar thermal collectors					
Install PV panels					
If there are any measures, please list and rate them					
Wind energy					
Use wind wind-assisted ventilation system					
Install wind turbine					
If there are any measures, please list and rate them					

Section 3: Statements on residential building NZC retrofitting.

Please indicate the level of agreement with the following statements in retrofitting the existing residential buildings to NZC. Use the following scale.

1 – strongly disagree
2 – disagree
3 – neutral
4 – agree
5 – strongly agree

Statement on residential building NZC retrofitting	Level of agreement				
	1	2	3	4	5
Lower the building maintenance costs					
Increase the building value					
Increased accessibility to incentives and subsidies					
Reduced energy costs					
Reduced environmental pollution					
Reduced energy consumption, energy saving, and secured energy supply					
Reduced CO_2 and GHG emissions					
Minimizing adverse climatic effects					
Improved building comfort (thermal, natural, lighting, acoustic, etc.)					
Increased the efficiency and reliability of the building system					
Increased building usable time					
Increased indoor and outdoor air quality					

Note: If you would like to receive a summary of the research findings, kindly provide your NAME and the EMAIL ADDRESS.

Name: ………………………….   Email: ………………………………

The End

Thank you for your generous participation!!!

Kind request: You may also forward this survey questionnaire to other colleagues or platforms that could contribute to the success of this research.

APPENDIX C

RETROFIT STRATEGIES WITHOUT COMBINING PV PANEL

	Wall Insulation (thickness (mm))	Wall shading (length (mm))	Double and triple-glazed windows with PVC frame (glass thickness (mm))	Air conditioner replacement
1	100	no	no	no
2	75	no	no	no
3	50	no	no	no
4	25	no	no	no
5	no	100	no	no
6	no	200	no	no
7	no	300	no	no
8	no	400	no	no
9	no	no	4,4	no
10	no	no	6,6	no
11	no	no	4,4,4	no
12	no	no	6,6,6	no
13	no	no	no	Replaced
14	100	100	no	no
15	100	200	no	no
16	100	300	no	no
17	100	400	no	no
18	100	no	4,4	no
19	100	no	6,6	no
20	100	no	4,4,4	no
21	100	no	6,6,6	no
22	100	no	no	Replaced
23	100	100	4,4	no
24	100	200	4,4	no
25	100	300	4,4	no
26	100	400	4,4	no
27	100	100	6,6	no
28	100	200	6,6	no
29	100	300	6,6	no
30	100	400	6,6	no
31	100	100	4,4,4	no
32	100	200	4,4,4	no
33	100	300	4,4,4	no
34	100	400	4,4,4	no
35	100	100	6,6,6	no
36	100	200	6,6,6	no
37	100	300	6,6,6	no
38	100	400	6,6,6	no
39	100	100	no	Replaced
40	100	200	no	Replaced
41	100	300	no	Replaced
42	100	400	no	Replaced
43	100	no	4,4	Replaced
44	100	no	6,6	Replaced
45	100	no	4,4,4	Replaced

46	100	no	6,6,6	Replaced
47	100	100	4,4	Replaced
48	100	200	4,4	Replaced
49	100	300	4,4	Replaced
50	100	400	4,4	Replaced
51	100	100	6,6	Replaced
52	100	200	6,6	Replaced
53	100	300	6,6	Replaced
54	100	400	6,6	Replaced
55	100	100	4,4,4	Replaced
56	100	200	4,4,4	Replaced
57	100	300	4,4,4	Replaced
58	100	400	4,4,4	Replaced
59	100	100	6,6,6	Replaced
60	100	200	6,6,6	Replaced
61	100	300	6,6,6	Replaced
62	100	400	6,6,6	Replaced
63	75	100	no	no
64	75	200	no	no
65	75	300	no	no
66	75	400	no	no
67	75	no	4,4	no
68	75	no	6,6	no
69	75	no	4,4,4	no
70	75	no	6,6,6	no
71	75	no	no	Replaced
72	75	100	4,4	no
73	75	200	4,4	no
74	75	300	4,4	no
75	75	400	4,4	no
76	75	100	6,6	no
77	75	200	6,6	no
78	75	300	6,6	no
79	75	400	6,6	no
80	75	100	4,4,4	no
81	75	200	4,4,4	no
82	75	300	4,4,4	no
83	75	400	4,4,4	no
84	75	100	6,6,6	no
85	75	200	6,6,6	no
86	75	300	6,6,6	no
87	75	400	6,6,6	no
88	75	100	no	Replaced
89	75	200	no	Replaced
90	75	300	no	Replaced
91	75	400	no	Replaced
92	75	no	4,4	Replaced
93	75	no	6,6	Replaced

94	75	no	4,4,4	Replaced
95	75	no	6,6,6	Replaced
96	75	100	4,4	Replaced
97	75	200	4,4	Replaced
98	75	300	4,4	Replaced
99	75	400	4,4	Replaced
100	75	100	6,6	Replaced
101	75	200	6,6	Replaced
102	75	300	6,6	Replaced
103	75	400	6,6	Replaced
104	75	100	4,4,4	Replaced
105	75	200	4,4,4	Replaced
106	75	300	4,4,4	Replaced
107	75	400	4,4,4	Replaced
108	75	100	6,6,6	Replaced
109	75	200	6,6,6	Replaced
110	75	300	6,6,6	Replaced
111	75	400	6,6,6	Replaced
112	50	100	no	no
113	50	200	no	no
114	50	300	no	no
115	50	400	no	no
116	50	no	4,4	no
117	50	no	6,6	no
118	50	no	4,4,4	no
119	50	no	6,6,6	no
120	50	no	no	Replaced
121	50	100	4,4	no
122	50	200	4,4	no
123	50	300	4,4	no
124	50	400	4,4	no
125	50	100	6,6	no
126	50	200	6,6	no
127	50	300	6,6	no
128	50	400	6,6	no
129	50	100	4,4,4	no
130	50	200	4,4,4	no
131	50	300	4,4,4	no
132	50	400	4,4,4	no
133	50	100	6,6,6	no
134	50	200	6,6,6	no
135	50	300	6,6,6	no
136	50	400	6,6,6	no
137	50	100	no	Replaced
138	50	200	no	Replaced
139	50	300	no	Replaced
140	50	400	no	Replaced
141	50	no	4,4	Replaced

142	50	no	6,6	Replaced
143	50	no	4,4,4	Replaced
144	50	no	6,6,6	Replaced
145	50	100	4,4	Replaced
146	50	200	4,4	Replaced
147	50	300	4,4	Replaced
148	50	400	4,4	Replaced
149	50	100	6,6	Replaced
150	50	200	6,6	Replaced
151	50	300	6,6	Replaced
152	50	400	6,6	Replaced
153	50	100	4,4,4	Replaced
154	50	200	4,4,4	Replaced
155	50	300	4,4,4	Replaced
156	50	400	4,4,4	Replaced
157	50	100	6,6,6	Replaced
158	50	200	6,6,6	Replaced
159	50	300	6,6,6	Replaced
160	50	400	6,6,6	Replaced
161	25	100	no	no
162	25	200	no	no
163	25	300	no	no
164	25	400	no	no
165	25	no	4,4	no
166	25	no	6,6	no
167	25	no	4,4,4	no
168	25	no	6,6,6	no
169	25	no	no	Replaced
170	25	100	4,4	no
171	25	200	4,4	no
172	25	300	4,4	no
173	25	400	4,4	no
174	25	100	6,6	no
175	25	200	6,6	no
176	25	300	6,6	no
177	25	400	6,6	no
178	25	100	4,4,4	no
179	25	200	4,4,4	no
180	25	300	4,4,4	no
181	25	400	4,4,4	no
182	25	100	6,6,6	no
183	25	200	6,6,6	no
184	25	300	6,6,6	no
185	25	400	6,6,6	no
186	25	100	no	Replaced
187	25	200	no	Replaced
188	25	300	no	Replaced
189	25	400	no	Replaced

190	25	no	4,4	Replaced
191	25	no	6,6	Replaced
192	25	no	4,4,4	Replaced
193	25	no	6,6,6	Replaced
194	25	100	4,4	Replaced
195	25	200	4,4	Replaced
196	25	300	4,4	Replaced
197	25	400	4,4	Replaced
198	25	100	6,6	Replaced
199	25	200	6,6	Replaced
200	25	300	6,6	Replaced
201	25	400	6,6	Replaced
202	25	100	4,4,4	Replaced
203	25	200	4,4,4	Replaced
204	25	300	4,4,4	Replaced
205	25	400	4,4,4	Replaced
206	25	100	6,6,6	Replaced
207	25	200	6,6,6	Replaced
208	25	300	6,6,6	Replaced
209	25	400	6,6,6	Replaced
210	no	100	4,4	no
211	no	200	4,4	no
212	no	300	4,4	no
213	no	400	4,4	no
214	no	100	6,6	no
215	no	200	6,6,	no
216	no	300	6,6,	no
217	no	400	6,6,	no
218	no	100	4,4,4	no
219	no	200	4,4,4	no
220	no	300	4,4,4	no
221	no	400	4,4,4	no
222	no	100	6,6,6	no
223	no	200	6,6,6	no
224	no	300	6,6,6	no
225	no	400	6,6,6	no
226	no	100	no	Replaced
227	no	200	no	Replaced
228	no	300	no	Replaced
229	no	400	no	Replaced
230	no	no	4,4	Replaced
231	no	no	6,6	Replaced
232	no	no	4,4,4	Replaced
233	no	no	6,6,6	Replaced
234	no	100	4,4	Replaced
235	no	200	4,4	Replaced
236	no	300	4,4	Replaced
237	no	400	4,4	Replaced

238	no	100	6,6	Replaced
239	no	200	6,6	Replaced
240	no	300	6,6	Replaced
241	no	400	6,6	Replaced
242	no	100	4,4,4	Replaced
243	no	200	4,4,4	Replaced
244	no	300	4,4,4	Replaced
245	no	400	4,4,4	Replaced
246	no	100	6,6,6	Replaced
247	no	200	6,6,6,	Replaced
248	no	300	6,6,6	Replaced
249	no	400	6,6,6	Replaced

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