

# **A Life Cycle Assessment Approach to Sustainable Building Design**

## **Developing strategies for green residential buildings in Cambodia**

A thesis submitted in partial fulfillment of the requirements  
for the degree of Doctor of Philosophy (PhD) in Engineering Science

by

**Makara LONG**



Supervisor: Sigrid REITER

Co-supervisor: Virak HAN

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This document presents the thesis research entitled:

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### **Composition of the jury for thesis defense:**

Prof. Dr. Sigrid REITER	University of Liège	Supervisor
Asst. Prof. Dr. Virak HAN	Institute of Technology of Cambodia	Co-supervisor
Prof. Dr. Angélique LÉONARD	University of Liège	Chair
Prof. Dr. Pierre LECLERCQ	University of Liège	Member
Asst. Prof. Dr. Sarin CHAN	Institute of Technology of Cambodia	Member
Prof. Dr. Dirk SCHWEDE	Technical University of Applied Sciences Lübeck	Member
Prof. Dr. Samia BEN RAJEB	Université Libre de Bruxelles	Member

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To my country, Cambodia កម្ពុជា,  
and my family.

# Abstract

The building sector is one of the largest consumers of energy and resources and a major contributor to waste generation and global greenhouse gas emissions. It has long been criticized for its inefficiency, slow innovation, and fragmented practices. As a result, achieving sustainable development in this sector remains a significant challenge. In Phnom Penh (Cambodia), the current construction boom has largely overlooked sustainable building practices, raising concerns about future environmental consequences. Addressing these issues requires a strong shift toward digitalization, green building practices, and enhanced stakeholder participation.

This PhD research investigates the contextual design characteristics and practices of green building and affordable housing within the Cambodian construction sector. It also evaluates the environmental impacts of buildings to identify optimal low-impact strategies and examines the applicability of simplified Life Cycle Assessment (LCA) methods to support decision-making at the early design stage. The research design was developed through a comprehensive literature review, followed by the formulation of research questions that guided the study. Both technical and socio-technical factors were considered to reflect real-world practices in local contexts. Data were collected through semi-structured interviews and analyzed alongside an LCA framework, with findings integrated during the interpretation phase.

The study identifies key contextual design characteristics for green and affordable housing, including architectural design, construction techniques, material and tool selection, financial considerations, and strategies for resource and energy conservation. Preferred residential typologies were also explored. Insights from 40 local construction professionals provided a comprehensive understanding of current practices and revealed opportunities for integrating LCA into green building design.

The environmental impacts of two residential buildings in Phnom Penh were assessed within defined system boundaries using SimaPro 9.4.0.2 software and the ecoinvent 3.8 database, following the Environmental Footprint 3.0 method. Sixteen environmental impact categories were evaluated. Four improvement scenarios were analyzed: material optimization and reduction of decorative elements; use of environmentally friendly and bio-based materials; adoption of lightweight timber structures; and integration of solar photovoltaic (PV) systems for renewable energy generation. Among these, the use of solar PV systems and lightweight timber structures demonstrated the most significant individual benefits. However, the combined application of all four strategies resulted in the greatest reduction in both carbon footprint and overall environmental impact. The study further compares three LCA approaches; screening, simplified, and complete, across two residential building typologies and six environmental indicators. The results indicate that simplified approaches, particularly screening LCA, can effectively support early-stage design decision-making.

Based on these findings, this research proposes context-specific recommendations for green and affordable housing design in Cambodia, along with low-impact building design strategies from a

life cycle perspective. It also highlights the potential of simplified LCAs as the practical decision-support tool for construction professionals, researchers, and students engaged in sustainable building design.

**Keywords:** Green building, Affordable housing, Life cycle assessment, Low-impact strategies, LCA simplification, Cambodia

# Résumé

Le secteur du bâtiment est l'un des plus gros consommateurs d'énergie et de ressources, et contribue fortement à la production de déchets et aux émissions mondiales de gaz à effet de serre. Il est depuis longtemps critiqué pour son inefficacité, la lenteur de ses innovations et la fragmentation de ses pratiques. En conséquence, parvenir à un développement durable dans ce secteur reste un défi de taille. À Phnom Penh (Cambodge), l'essor actuel de la construction a largement négligé les pratiques de construction durable, ce qui soulève des inquiétudes quant aux conséquences environnementales futures. Pour répondre à ces enjeux, un virage décisif vers la numérisation, les pratiques de construction écologiques et une participation accrue des parties prenantes s'impose.

Cette thèse de doctorat examine les caractéristiques contextuelles de conception et les pratiques en matière de construction écologique et de logements abordables au sein du secteur de la construction cambodgien. Elle évalue également les impacts environnementaux des bâtiments afin d'identifier des stratégies optimales à faible impact et examine l'applicabilité de méthodes simplifiées d'analyse du cycle de vie (ACV) pour soutenir la prise de décision dès les premières étapes de la conception. Le plan de recherche a été élaboré à partir d'une revue exhaustive de la littérature, suivie de la formulation de questions de recherche qui ont guidé l'étude. Des facteurs à la fois techniques et socio-techniques ont été pris en compte afin de refléter les pratiques réelles dans les contextes locaux. Les données ont été recueillies au moyen d'entretiens semi-structurés et analysées à l'aide d'un cadre d'ACV, les résultats ayant été intégrés lors de la phase d'interprétation.

Cette étude identifie les principales caractéristiques contextuelles de conception des logements écologiques et abordables, notamment la conception architecturale, les techniques de construction, le choix des matériaux et des outils, les considérations financières, ainsi que les stratégies de conservation des ressources et de l'énergie. Les typologies résidentielles privilégiées ont également été examinées. Les contributions de 40 professionnels locaux du secteur de la construction ont permis d'acquérir une compréhension globale des pratiques actuelles et ont mis en évidence des possibilités d'intégrer l'analyse du cycle de vie (ACV) dans la conception de bâtiments écologiques.

Les impacts environnementaux de deux bâtiments résidentiels à Phnom Penh ont été évalués dans des limites de système définies à l'aide du logiciel SimaPro 9.4.0.2 et de la base de données ecoinvent 3.8, conformément à la méthode Environmental Footprint 3.0. Seize catégories d'impacts environnementaux ont été évaluées. Quatre scénarios d'amélioration ont été analysés : l'optimisation des matériaux et la réduction des éléments décoratifs ; l'utilisation de matériaux respectueux de l'environnement et d'origine biologique ; l'adoption de structures légères en bois ; et l'intégration de systèmes solaires photovoltaïques (PV) pour la production d'énergie renouvelable. Parmi ceux-ci, l'utilisation de systèmes solaires photovoltaïques et de structures légères en bois a démontré les avantages individuels les plus significatifs. Cependant, l'application

combinée des quatre stratégies a entraîné la plus forte réduction tant de l'empreinte carbone que de l'impact environnemental global. L'étude compare en outre trois approches d'ACV (analyse du cycle de vie) : l'approche de dépistage, l'approche simplifiée et l'approche complète, pour deux typologies de bâtiments résidentiels et six indicateurs environnementaux. Les résultats indiquent que les approches simplifiées, en particulier l'ACV de dépistage, peuvent efficacement soutenir la prise de décision en matière de conception dès les premières étapes.

Sur la base de ces résultats, cette étude propose des recommandations adaptées au contexte pour la conception de logements écologiques et abordables au Cambodge, ainsi que des stratégies de conception de bâtiments à faible impact environnemental dans une perspective de cycle de vie. Elle met également en évidence le potentiel des ACV simplifiées en tant qu'outil pratique d'aide à la décision pour les professionnels du bâtiment, les chercheurs et les étudiants impliqués dans la conception de bâtiments durables.

**Mots-clés :** Bâtiment écologique, Logement abordable, Analyse du cycle de vie, Stratégies à faible impact, ACV simplifiée, Cambodge

# សង្ខេប

វិស័យសំណង់អគារគឺជាវិស័យមួយក្នុងចំណោមវិស័យដែលប្រើប្រាស់ថាមពល និងធនធានច្រើនជាងគេ ហើយក៏ជាកត្តា រួមចំណែកដ៏សំខាន់មួយចំពោះការបង្កើតកាកសំណល់ និងការបំបាត់ឧស្ម័នផ្ទះកញ្ចក់ទូទាំងពិភពលោក។ វាត្រូវបានគេរិះ គន់ជាយូរមកហើយចំពោះភាពគ្មានប្រសិទ្ធភាព ការច្នៃប្រឌិតយឺត និងការអនុវត្តដែលបែកបាក់។ ជាលទ្ធផល ការសម្រេច បាននូវការអភិវឌ្ឍប្រកបដោយចីរភាពនៅក្នុងវិស័យនេះនៅតែជាបញ្ហាប្រឈមដ៏សំខាន់មួយ។ នៅទីក្រុងភ្នំពេញ ការរីក ចម្រើននៃវិស័យសំណង់អគារបច្ចុប្បន្នភាគច្រើនបានមើលរំលងការអនុវត្តការសាងសង់ប្រកបដោយនិរន្តរភាព ដែលបង្កើន ការព្រួយបារម្ភអំពីផលវិបាកបរិស្ថាននាពេលអនាគត។ ការដោះស្រាយបញ្ហាទាំងនេះតម្រូវឱ្យមានការផ្លាស់ប្តូរយ៉ាងខ្លាំង ឆ្ពោះទៅរកឌីជីថលលូបនីយកម្ម ការអនុវត្តអគារបៃតង និងការចូលរួមពីភាគីពាក់ព័ន្ធកាន់តែប្រសើរឡើង។

ការស្រាវជ្រាវថ្នាក់បណ្ឌិតនេះស៊ើបអង្កេតលក្ខណៈរចនាបរិបទ និងការអនុវត្តនៃអគារបៃតង និងលំនៅឋានដែលមានតម្លៃ សមរម្យនៅក្នុងវិស័យសំណង់កម្ពុជា។ ការស្រាវជ្រាវនេះក៏វាយតម្លៃផលប៉ះពាល់បរិស្ថាននៃអគារ ដើម្បីកំណត់យុទ្ធសាស្ត្រ ដែលមានផលប៉ះពាល់ទាបល្អបំផុត និងពិនិត្យមើលការអនុវត្តវិធីសាស្ត្រវាយតម្លៃវដ្តជីវិតលក្ខណៈសាមញ្ញ ដើម្បីគាំទ្រដល់ ការធ្វើការសម្រេចចិត្តនៅដំណាក់កាលរចនាដំបូងនៃគម្រោងសំណង់អគារ។ ការរចនាការស្រាវជ្រាវត្រូវបានបង្កើតឡើង តាមរយៈការសំយោគឯកសារពាក់ព័ន្ធដ៏ទូលំទូលាយ បន្ទាប់មកដោយការបង្កើតសំណួរស្រាវជ្រាវដែលបានណែនាំការ សិក្សា។ ទាំងកត្តាបច្ចេកទេស និងសង្គម-បច្ចេកទេសត្រូវបានចាត់ទុកថាផ្ទះបញ្ចាំងពីការអនុវត្តជាក់ស្តែងនៅក្នុងបរិបទក្នុង ស្រុក។ ទិន្នន័យត្រូវបានប្រមូលតាមរយៈការសម្ភាសន៍ពាក់កណ្តាលរចនាសម្ព័ន្ធ និងវិភាគរួមជាមួយនឹងក្របខ័ណ្ឌវាយតម្លៃ វដ្តជីវិត ជាមួយនឹងការរកឃើញដែលបានរួមបញ្ចូលក្នុងដំណាក់កាលបកស្រាយ។

ការសិក្សានេះកំណត់អត្តសញ្ញាណលក្ខណៈរចនាបរិបទសំខាន់ៗសម្រាប់លំនៅឋានបៃតងដែលមានតម្លៃសមរម្យ រួមទាំង ការរចនាស្ថាបត្យកម្ម បច្ចេកទេសសាងសង់ ការជ្រើសរើសសម្ភារៈ និងឧបករណ៍ ការពិចារណាផ្នែកហិរញ្ញវត្ថុ និងយុទ្ធសា ស្ត្រសម្រាប់ការអភិរក្សធនធាន និងថាមពល។ ប្រភេទអគារលំនៅឋានដែលសាកសមពេញចិត្តក៏ត្រូវបានស្វែងយល់ផងដែរ ។ ការយល់ឃើញពីអ្នកជំនាញផ្នែកសំណង់ក្នុងស្រុកចំនួន ៤០ នាក់បានផ្តល់នូវការយល់ដឹងយ៉ាងទូលំទូលាយអំពីការអនុ វត្តបច្ចុប្បន្ន និងបានបង្ហាញពីឱកាសសម្រាប់ការរួមបញ្ចូលវិធីសាស្ត្រវាយតម្លៃវដ្តជីវិតទៅក្នុងការរចនាអគារបៃតង។

ផលប៉ះពាល់បរិស្ថាននៃអគារលំនៅឋានពីរកន្លែងនៅក្នុងទីក្រុងភ្នំពេញ ត្រូវបានវាយតម្លៃនៅក្នុងព្រំដែនប្រព័ន្ធដែលបាន កំណត់ ដោយប្រើកម្មវិធី SimaPro 9.4.0.2 និងមូលដ្ឋានទិន្នន័យ ecoinvent 3.8 ដោយអនុវត្តតាមវិធីសាស្ត្រ Environmental Footprint 3.0។ ប្រភេទផលប៉ះពាល់បរិស្ថានចំនួន ១៦ ត្រូវបានវាយតម្លៃ។ សេណារីយ៉ោកែលម្អចំនួន បួនត្រូវបានវិភាគ៖ ការបង្កើនប្រសិទ្ធភាពសម្ភារៈ និងការកាត់បន្ថយគ្រឿងតុបតែង; ការប្រើប្រាស់សម្ភារៈដែលមិនប៉ះពាល់ ដល់បរិស្ថាន និងផ្នែកលើដីសាស្ត្រ; ការទទួលប្រើគ្រឿងបង្កើនលើទម្ងន់ស្រាល; និងការរួមបញ្ចូលប្រព័ន្ធ photovoltaic ពន្លឺ ព្រះអាទិត្យសម្រាប់ការបង្កើតថាមពលកកើតឡើងវិញ។ ក្នុងចំណោមយុទ្ធសាស្ត្រទាំងនេះ ការប្រើប្រាស់ប្រព័ន្ធ photovoltaic ពន្លឺព្រះអាទិត្យ និងគ្រឿងបង្កើនលើទម្ងន់ស្រាលបានបង្ហាញពីអត្ថប្រយោជន៍សំខាន់បំផុត។ ទោះជាយ៉ាងណា ក៏ដោយ ការអនុវត្តរួមគ្នានៃយុទ្ធសាស្ត្រទាំងបួនខាងលើបាននាំឱ្យមានការថយចុះច្រើនបំផុតទាំងផលប៉ះពាល់ដានកាបូន និងផលប៉ះពាល់បរិស្ថានទាំងមូល។ ការសិក្សានេះប្រៀបធៀបបន្ថែមទៀតនូវវិធីសាស្ត្រវាយតម្លៃវដ្តជីវិត ចំនួនបី; Screening, Simplified, និង Complete ទៅលើប្រភេទអគារលំនៅឋានទាំងពីរ និងសូចនាករបរិស្ថានចំនួនប្រាំមួយ។

លទ្ធផលបង្ហាញថា វិធីសាស្ត្រសាមញ្ញ ជាពិសេស Screening LCA អាចគាំទ្រដល់ការសម្រេចចិត្តរចនាអគារដំណាក់កាល ដំបូងប្រកបដោយប្រសិទ្ធភាព។

ដោយផ្អែកលើការរកឃើញទាំងនេះ ការស្រាវជ្រាវនេះស្នើជាអនុសាសន៍ជាក់លាក់តាមបរិបទសម្រាប់ការរចនាលំនៅឋាន បែតង និងមានតម្លៃសមរម្យនៅក្នុងប្រទេសកម្ពុជា រួមជាមួយនឹងយុទ្ធសាស្ត្ររចនាអគារដែលមានផលប៉ះពាល់ទាបពីទស្សនៈវដ្តជីវិត។ វាក៏បានបង្ហាញពីសក្តានុពលនៃវិធីសាស្ត្រវាយតម្លៃវដ្តជីវិតលក្ខណៈសាមញ្ញ ជាឧបករណ៍គាំទ្រការសម្រេចចិត្ត ជាក់ស្តែងសម្រាប់អ្នកជំនាញផ្នែកសំណង់ អ្នកស្រាវជ្រាវនិងនិស្សិតដែលចូលរួមក្នុងការរចនាអគារប្រកបដោយនិរន្តរភាព។

**ពាក្យគន្លឹះ៖** អគារបែតង លំនៅឋានដែលមានតម្លៃសមរម្យ វិធីសាស្ត្រវាយតម្លៃវដ្តជីវិត យុទ្ធសាស្ត្រផលប៉ះពាល់បរិស្ថាន ទាប សាមញ្ញភាពនៃវិធីសាស្ត្រវាយតម្លៃវដ្តជីវិត កម្ពុជា

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Makara LONG  
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# 1

## Introduction

Welcome to the first chapter of this thesis, which presents the research background, context, rationale, approach, and significance of the study. The aim and motivation are developed in relation to the identified problem statement and research focus. The research questions and objectives are also outlined in this chapter. Finally, the structure of the manuscript is presented to guide the reader through the overall flow of the thesis.

## 1.1 RESEARCH BACKGROUND

The built environment including the construction industry, buildings, and infrastructure plays a crucial role in driving economic and social development. However, the buildings and construction sector are also a major contributor to environmental degradation due to its high energy consumption, resource depletion, greenhouse gas (GHG) emissions, solid waste generation, adverse health impacts, and land use pressures (Crawford, 2011; Kiasif1 & Doran, 2023). While the sector forms the physical foundation of urban development and supports socio-economic growth, its environmental footprint remains substantial.

As of early 2025, the buildings and construction sector continue to account for a significant share of global energy-related CO<sub>2</sub> emissions, including those associated with the embodied carbon of construction materials. The sector is responsible for approximately 34% of global CO<sub>2</sub> emissions and 34% of global energy consumption, while also generating nearly 40% of solid waste worldwide (UNEP, 2011, 2025). Despite some progress, the sector remains off track in achieving net-zero carbon and climate resilience targets by 2050. Since 2015, CO<sub>2</sub> emissions from the sector have increased by 5%, far from the 28% reduction required by 2030 to align with the Paris Agreement (UNEP, 2025). Furthermore, the share of embodied carbon emissions is expected to grow due to increasing infrastructure development, building construction, and ambitious retrofit targets (Mirzaie, 2022). These trends highlight the urgent need for improved sustainability measures, innovative building design strategies, and effective assessment tools.

In response to these environmental challenges, the concepts of sustainability and sustainable development have gained global prominence. The term “sustainable development” was first formally introduced in the United Nations’ report *Our Common Future* (World Commission on Environment and Development, 1987), where it was defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Since then, numerous global initiatives have been launched to promote sustainable development across environmental, social, and economic dimensions. Notably, the United Nations established the Sustainable Development Goals (SDGs) in 2015, setting a global agenda to be achieved by 2030.

As a developing country, Cambodia has increasingly aligned its development strategies with the SDGs, particularly in the construction sector (NCSD/Ministry of Environment of Cambodia, 2018). However, challenges such as natural resource depletion, rising energy demand, and increasing temperatures continue to pose significant barriers. In response to global climate commitments, Cambodia has pledged under the Paris Agreement to achieve carbon neutrality by 2050 (Mazzoli et al., 2025). This commitment is supported by several national policies, including the Nationally Determined Contributions (NDC), which targets a 42% reduction in GHG emissions by 2030 (Ministry of Environment, 2020), the National Energy Efficiency Policy, which aims for at least a 19% reduction in energy consumption by 2030 (National Committee on Energy Efficiency, 2022), and the Long-Term Strategy for Carbon Neutrality (Ministry of Environment of Cambodia, 2021).

These initiatives emphasize the need for sustainable construction practices, improved energy efficiency, and reduced environmental impacts across sectors in Cambodia.

At the urban scale, the Phnom Penh Sustainable City Plan (2018) reflects Cambodia's commitment to integrating sustainability into urban development, aiming to enhance economic growth and quality of life (NCSD/Ministry of Environment of Cambodia et al., 2018). Additionally, the Ministry of Environment has initiated the development of Cambodia's Guidelines and Certification for Green Building (CamGCCB) to promote sustainable architecture and construction practices (NCSD/Ministry of Environment of Cambodia, 2021). Although still under development, this framework represents an important step toward institutionalizing green building practices. Furthermore, the Cambodia Green Building Council (CamGBC) has been established as an independent, non-profit organization to support similar objectives (CamGBC, 2026). Despite these initiatives, current approaches tend to emphasize policy and social dimensions, with comparatively limited focus on technical and environmental performance aspects.

Globally, increasing demand for buildings has driven the development of various sustainability-oriented approaches, including green buildings, zero-energy buildings, passive houses, and carbon-neutral buildings (Allacker et al., 2013). Green buildings also referred to as sustainable buildings are generally defined as buildings that are designed, constructed, and operated to optimize energy and material efficiency while minimizing environmental impacts. Over the past two decades, the adoption of green building practices has increased significantly worldwide (Baloch et al., 2022; Chen et al., 2021). These buildings are associated with positive environmental, economic, and social outcomes throughout their life cycle (Ahmad et al., 2016). Common elements of green building definitions include life cycle thinking, environmental sustainability, occupant health, and community impact (Zuo & Zhao, 2014).

A key methodological approach for evaluating and achieving green building performance is Life Cycle Assessment (LCA) (Faiz Musa et al., 2014; Zuo & Zhao, 2014). LCA provides a systematic framework for assessing the environmental impacts of buildings across all life cycle stages, from material production to end of life. By integrating LCA into building design and decision-making processes, professionals can evaluate alternative materials, components, and systems, and identify strategies to reduce environmental impacts.

Construction professionals and stakeholders play a central role in advancing green building practices within specific regional contexts (Darko et al., 2017; Long et al., 2024). The adoption and implementation of green building strategies are highly context-dependent, influenced by factors such as climate conditions, socio-economic context, regulatory frameworks, and stakeholder capacity (Chan et al., 2017). Moreover, the knowledge, perceptions, attitudes, and experiences of professionals significantly shape the uptake of sustainable construction practices. Therefore, understanding how green building is defined and practiced within the Cambodian context is essential for promoting its effective implementation.

In parallel, the development of affordable housing remains a critical priority for Cambodia's socio-economic development. Rapid population growth and urbanization are driving increased demand

for housing, a trend observed globally (Oyamo & Oyatomu, 2025; World Green Building Council, 2026). The global urban population is projected to nearly double by 2050 (UN-Habitat, 2022), and by 2070, approximately 58% of the world's population is expected to live in urban areas (Muhammed et al., 2025). Without adequate infrastructure, housing, and urban planning, this rapid urbanization could exacerbate congestion and strain urban systems. In developing countries, including Cambodia, vulnerability to natural disasters further emphasizes the need for safe, resilient, and affordable housing solutions. The integration of green building principles with affordable housing, referred to as green affordable housing, introduces additional complexity, requiring careful consideration of economic, environmental, and social factors. Successful implementation depends on the collaboration of multiple stakeholders, particularly construction professionals, whose expertise is essential for translating sustainability concepts into practical design solutions (Karamoozian & Zhang, 2025; Reid, 2023).

Finally, the growing application of LCA in the building sector reflects increasing awareness of environmental impacts and the need for evidence-based decision-making. Numerous studies have demonstrated the effectiveness of LCA in reducing energy and material consumption, as well as associated environmental impacts (Abd Rashid & Yusoff, 2015; Singh et al., 2011). From a sustainable development perspective, building performance must be evaluated across the entire life cycle, including design, production, construction, operation, and end of life stages (Ingrao et al., 2018; Reiter, 2010). As a widely recognized tool, LCA enables the assessment of resource use and emission flows throughout a building's lifespan (Feng et al., 2023; Nematchoua & Reiter, 2019b, 2019a), thereby supporting more informed and sustainable design decisions.

### **1.1.1 Problem statement**

The construction boom in Cambodia has accelerated since the early 2000s, driven by rapid urban growth and significant internal migration from rural provinces to urban centers, particularly Phnom Penh. This demographic shift has increased the demand for infrastructure, public facilities, and housing (Taing, 2024; Thuon, 2021). As the capital city, Phnom Penh has experienced the most intensive construction activity in the country, with residential buildings representing a dominant share of the building stock and a primary focus for developers and investors. In recent years, there has been a marked transformation in the urban housing landscape, characterized by the rapid expansion of high-rise apartments, condominiums, and gated communities (locally known as Borey developments). These typologies are increasingly replacing traditional low-rise and detached housing forms. Their presence is now visible across both central and peripheral urban areas. Based on building approval data and current development trends, this typology is expected to continue expanding until at least 2035, with numerous residential projects already planned or under development (NCSA/Ministry of Environment of Cambodia, 2021).

Although Cambodia has a strong tradition of climate-responsive vernacular architecture, such as traditional Khmer houses and early modern Khmer architectural expressions (New Khmer Architecture), there is currently limited application and awareness of sustainable building

principles within the contemporary construction sector. The ongoing construction boom in Phnom Penh is increasingly characterized by insufficient attention to environmental sustainability, raising concerns about long-term environmental and socio-economic consequences (Waibel, 2017). One key issue is that building design in Cambodia tends to prioritize architectural form and aesthetics over functionality, environmental performance, and occupant comfort. As a result, many vernacular design principles have been gradually replaced by modern construction practices that often lead to poorer indoor environmental quality, increased reliance on imported materials, higher energy consumption, and reduced user comfort. These outcomes are partly attributable to limited knowledge, technical capacity, and awareness among construction professionals and stakeholders (On & Techapeeraparnich, 2021; Schoch et al., 2025). Consequently, although some architects and engineers attempt to incorporate sustainable design principles, their application remains limited and inconsistent across the sector.

Furthermore, green and low-impact design strategies remain relatively unfamiliar to many stakeholders, including designers, developers, and occupants. These challenges are compounded by the absence of comprehensive guidelines and regulatory frameworks for sustainable building design. As a result, a large proportion of residential buildings in Cambodia are constructed with a primary focus on cost reduction, often without the involvement of qualified architects or structural engineers. For example, townhouse typologies such as link houses or shophouses are frequently replicated from existing designs with minimal technical adaptation or design optimization. Similarly, larger-scale residential projects rarely incorporate systematic design analysis or performance simulations related to energy efficiency, indoor environmental quality, or carbon emissions. Such assessments are typically conducted only in a limited number of projects, primarily for the purpose of obtaining green building certification. Consequently, current green building practices in Cambodia tend to focus narrowly on passive design strategies such as natural ventilation and daylighting, while neglecting deeper considerations such as material selection, life cycle resource efficiency, renewable energy integration, and low-carbon construction practices.

From an energy and resource perspective, the Cambodian construction sector accounts for approximately 52% of national energy consumption (Joint SDG Fund, 2025), while imports of construction materials increased by 35.6% in 2025 (Construction Property, 2025). These trends highlight a rapidly growing resource demand in the absence of effective low-carbon transition strategies.

Although new residential developments such as apartments and gated communities aim to address housing demand, affordability remains a critical challenge. More than 60% of the population in Phnom Penh cannot afford formal housing (GGGI et al., 2022). This issue is further exacerbated by the absence of effective policies, limited stakeholder collaboration, and a lack of technical and design guidance for affordable housing development (Long et al., 2024). Beyond affordability, sustainability considerations, such as energy efficiency, water conservation, waste reduction, and environmental performance, are not sufficiently integrated into housing design and development processes (GGGI, 2022). The limited integration of sustainable design principles

in affordable housing not only contributes to high construction costs but also overlooks the potential contributions of design professionals in improving building performance and quality of life. As a result, many housing projects suffer from inadequate occupant comfort, limited access to services and infrastructure, high operational energy and water consumption, and suboptimal construction quality. These issues reflect a broader systemic gap in the integration of sustainability principles during the design stage, particularly in relation to affordability and livability.

Overall, these challenges highlight the limited development and implementation of green building and affordable housing practices in Cambodia. This situation is largely driven by low awareness of long-term environmental and economic benefits, as well as insufficient technological support and institutional capacity (Durdyev et al., 2018; Taing, 2024). In addition, Cambodia currently lacks widely adopted tools and methodologies for assessing building environmental performance, such as LCA, despite its established use in many developed countries (Jayawardana et al., 2023; Long et al., 2025; Ortiz-Rodríguez et al., 2010). As a result, benchmark data on building environmental impacts, including life cycle CO<sub>2</sub> emissions, remain largely unavailable in the Cambodian context.

Although LCA has been increasingly recognized as a valuable decision-support tool in the construction sector, its application in developing countries and more specifically in Cambodia remains limited due to several barriers. First, conducting a complete LCA is time-consuming and resource-intensive, particularly in relation to embodied impacts of construction materials. Unlike manufactured products, buildings consist of numerous interconnected components and materials, making system boundaries complex to define (Bonnet et al., 2014). Second, the absence of standardized procedures and harmonized data leads to significant variability in results. Differences in system boundaries, data quality, and user expertise can result in inconsistent outcomes, even when using the same tools. Therefore, there is a clear need to develop harmonized and simplified LCA approaches tailored to the construction sector, particularly in developing contexts such as Cambodia. Such approaches should enable more accessible, consistent, and efficient evaluation of building environmental impacts, while supporting early-stage design decision-making. The development of simplified LCA frameworks is therefore essential to facilitate broader adoption of life cycle thinking and to support the transition toward low-carbon and sustainable building practices in Cambodia.

### **1.1.2 Aim and motivation**

The motivation for this PhD research arises from increasing concerns regarding the environmental performance of buildings, particularly the environmental impacts associated with residential construction in Cambodia. As a developing country experiencing rapid urbanization, Cambodia faces continuous growth in construction activity to meet rising population demands. However, this growth has not been matched by the widespread adoption of energy- and material-efficient or low-impact building design practices. As a result, there is a growing risk of increased

embodied carbon, operational energy consumption, pollution, and other associated environmental impacts.

In response to these challenges, the global aim of this research is to identify the contextual characteristics of green and affordable building design in Cambodia and to develop strategies that can reduce life cycle environmental impacts related to residential buildings, while also exploring LCA simplification tools to support green building design in Cambodia. The study investigates the current contextual understanding of key building concepts, namely green building, affordable housing, and their integration within the Cambodian construction sector, in order to understand how these concepts are interpreted and applied by local construction professionals. Furthermore, this research seeks to evaluate the environmental impacts of residential buildings in Cambodia using LCA, and to identify design strategies that can effectively reduce these impacts across the building life cycle. In addition to improving the environmental performance of residential buildings, the study also introduces and evaluates simplification LCA approaches as decision-support tools during the early design stage. These tools aim to increase awareness and facilitate the practical application of low-impact and sustainable design strategies among construction professionals.

By integrating both contextual and environmental analyses, this research aspires to bridge the gap between sustainability concepts and practical implementation in the Cambodian construction sector. The findings are intended to support policymakers in developing more informed regulations and guidelines, while also assisting construction professionals in achieving long-term industry goals related to low-carbon and sustainable construction. Ultimately, this study promotes the adoption of life cycle thinking and green building approaches in residential building design within the Cambodian context.

## 1.2 RESEARCH OBJECTIVES

The primary focus of this thesis is to address the environmental impacts of conventional residential buildings in Cambodia. The overall aim of this research is to identify green building design strategies, evaluated through LCA, in order to reduce building life cycle environmental impacts. To support this aim, a simplified LCA approach is evaluated by comparison to the complete LCA framework because it could serve as a decision-support tool to assist construction professionals in evaluating environmental impacts and testing design alternatives during the early stages of building design.

Accordingly, the core objectives of this research are as follows:

- 1) To identify the contextual definitions and characteristics of green building and affordable housing design, including key focus areas and relevant aspects of their integration to achieve green affordable housing, from the perspectives of construction professionals in Cambodia.

- 2) To evaluate and establish a benchmark of conventional residential buildings in Cambodia in terms of sixteen environmental impact categories across their life cycle, using LCA.
- 3) To identify and define optimal building design strategies aimed at reducing their life cycle environmental impacts, based on LCA evaluation.
- 4) To evaluate the usefulness of LCA simplification to facilitate the assessment of building environmental impacts and the comparison of design strategies and alternatives during the early building design stage, with the hope that simplified LCA could become a decision-making tool during the building design process.

### 1.3 RESEARCH QUESTIONS

Accordingly, the research questions are as follows:

- 1) How are affordable housing and green building defined and characterized within the Cambodian construction sector?
- 2) What are the key priorities and considerations related to architectural design, construction techniques, material selection, construction cost and sale price, residential typologies, and other relevant aspects in the design of green affordable housing in Cambodia, from the perspective of construction professionals?
- 3) How can the environmental impacts of residential buildings in Cambodia be quantitatively assessed across their life cycle using LCA?
- 4) Which building design strategies are most effective in reducing the life cycle environmental impacts of residential buildings in Cambodia?
- 5) To what extent can LCA simplification approaches be used to estimate building environmental impacts and evaluate low-impact design alternatives during the early design stage?

To answer these research questions, this study first explores the contextual definitions and characteristics of green building and affordable housing in Cambodia, as perceived by local construction professionals with diverse expertise. In addition, it investigates the key design considerations relevant to the development of green affordable housing. This first part of the research aims to answer research questions 1 and 2.

The study further addresses LCA-related questions focusing on the quantitative evaluation of environmental impacts from residential buildings in Cambodia. These questions aim to identify building design strategies that effectively reduce life cycle environmental impacts and to determine optimal solutions. In addition, the study examines the potential application of LCA simplification approaches for evaluating environmental performance and testing design alternatives during the building early design stage. These research aspects aim to address research questions 3 to 5.

## 1.4 RESEARCH APPROACH

The research methodology was developed through an extensive literature review and follows a pragmatic, mixed-methods approach aligned with the research objectives. Both qualitative and quantitative methods were employed, operating relatively independently, with integration occurring during the interpretation phase. The methods include: (i) literature review on green building, affordable housing, LCA applications in the building sector, and LCA simplification approaches; (ii) semi-structured interviews with construction professionals; and (iii) LCA, including three levels of analysis (screening, simplified, and complete LCA).

Using a qualitative research method, the study investigates current practices and contextual characteristics of green building and affordable housing design in Cambodia from the perspectives of construction professionals, including architects, civil engineers, green building experts, and decision-makers. Other stakeholder groups, such as end-users and residents, were not included in this phase. Data were collected through one-to-one semi-structured interviews, following a mixed epistemological orientation combining positivist and interpretivist perspectives. The interview design was grounded in a constructivist ontological framework, aiming to capture the subjective perceptions and experiences of professionals within the Cambodian construction context. The interviews explored participants' understanding of green building, affordable housing, and their integration, as well as related design and implementation considerations. This qualitative analysis was essential for identifying contextual characteristics of local building practices and for understanding the current state of sustainable construction in Cambodia. The findings were subsequently used to inform and complement the LCA-based quantitative results, particularly in the formulation of design recommendations.

Then, the quantitative research approach is applied on case-study buildings to evaluate their environmental impacts and potential green strategies to improve their performance. The case-study buildings, comprising a townhouse and an apartment building, were systematically selected and investigated through on-site data collection. Key data were gathered, including building specifications, construction characteristics, and monthly electricity and water consumption. The selection of case-study buildings was based on several criteria, including their relevance as dominant residential typologies in Cambodia, location within Phnom Penh, construction period (within the last 20 years to the present), data availability, accessibility for field investigation, and the possibility of obtaining permission from building owners or responsible parties. On-site surveys and measurements were conducted to collect comprehensive building data and to ensure the accuracy and completeness of information, particularly regarding material types and building components. These data were essential for evaluating building performance in terms of life cycle environmental impacts.

LCA is a standardized environmental assessment tool used to quantify environmental impacts associated with all stages of a product or system life cycle, from raw material extraction to end of life disposal. In this study, LCA was applied to establish a benchmark of sixteen environmental impact categories for conventional residential buildings in Cambodia and to identify optimal

design strategies for reducing their life cycle environmental impacts, including both material- and energy-related interventions. The environmental performance of the selected case-study buildings was evaluated using the LCA method, and more specifically SimaPro 9.4.0.2 software and the ecoinvent 3.8 database, following the Environmental Footprint (EF) 3.0 framework.

In addition, the study explores LCA simplification approaches as decision-support tools for early-stage building design. These approaches aim to facilitate rapid assessment of environmental impacts and enable the testing of low-impact design alternatives with reduced data requirements. The results of the LCA analysis are intended to serve as preliminary regional benchmark values for residential buildings in Cambodia, a developing country in Southeast Asia. Furthermore, the study compares the outcomes of three levels of LCA detail: screening, simplified, and complete LCA, through comparative analysis at the levels of building components, materials, impact categories, and life cycle stages.

Finally, parameters outside the defined scope of this research were excluded and are acknowledged as limitations of the study. A more detailed description of the research methodology is provided in Chapter 3.

## 1.5 MAIN INNOVATION

To date, the practice and implementation of green building design within the Cambodian construction sector remain limited. Similarly, affordable housing development is still constrained in terms of both quantity and quality, often failing to provide adequate housing conditions for local residents. In addition, the involvement of construction professionals in providing technical and design input, particularly with regard to sustainability considerations, remains insufficient. Furthermore, although LCA is widely recognized as a key methodology for assessing building environmental performance in the world, no comprehensive LCA study has yet been conducted for residential buildings in Cambodia.

Based on the research findings, the main innovations and significant contributions of this doctoral research are as follows:

- Development of contextual definitions, characteristics, and relevant aspects of green building design in Cambodia, including construction cost, sale price, representative project examples, and insights from local professional practice.
- Development of contextual definitions, characteristics, and relevant aspects of affordable housing in Cambodia, including construction cost, sale price, design considerations, and relevant project examples.
- Identification of key priorities and design considerations for green affordable housing in Cambodia, including construction cost, sale price, material selection, design approaches, tools and technologies, preferred residential typologies, and locally relevant case examples.

- Establishment of a benchmark for sixteen environmental impact categories of two types of conventional residential buildings in Cambodia using LCA, including documentation of methodology, data sources, tools, databases, and key limitations and challenges encountered.
- Identification of optimal building design strategies for reducing life cycle environmental impacts of residential buildings in Cambodia, incorporating both material- and energy-related scenarios evaluated through LCA.
- Evaluation of LCA simplification approach to assist construction professionals in evaluating environmental impacts and testing low-impact design alternatives during the early stages of building design.

## 1.6 RESEARCH OUTLINE

The manuscript of this PhD thesis consists of nine chapters, including this introductory chapter which presents the research background, motivation, objectives, five specific research questions, and the main innovation of the thesis. The remaining chapters are structured as follows:

- Chapter 2 presents the literature review, covering existing studies on green building concepts and approaches, the affordable housing sector, current practices and design strategies, identified research gaps, LCA applications in the building industry, and LCA simplification approaches.
- Chapter 3 describes the research methodology and outlines the procedures used to address the research questions and achieve the research objectives.
- Chapter 4 investigates the integration of green building and affordable housing design in Cambodia, focusing on contextual characteristics and key design aspects from the perspectives and experiences of local construction professionals.
- Chapter 5 presents an LCA of a townhouse case study in Cambodia within a defined system boundary. This chapter includes the evaluation of sixteen environmental impact categories, the assessment of proposed design strategies for reducing life cycle impacts, and the identification of optimal strategies.
- Chapter 6 presents a complete LCA of a high-rise apartment building in Cambodia. It includes the evaluation of sixteen environmental impact categories, analysis of design strategies for reducing environmental impacts, and detailed results by building components, materials, life cycle stages, and modules. Key findings and potential improvements are also discussed.
- Chapter 7 presents a comparative LCA analysis of the two case studies. This includes a comparison of environmental impacts between building typologies, as well as a comparative assessment of three LCA approaches: screening, simplified, and complete LCA, across six impact indicators. The chapter also analyses result deviations and evaluates the applicability of LCA simplification tools.
- Chapter 8 discusses the main findings in relation to the research questions and objectives, and reflects on the methodological approach, limitations, and case-study constraints.

Chapter 9 presents the overall conclusions of the PhD thesis and provides recommendations for future research.

Finally, the PhD thesis also includes a detailed bibliography and three appendices.

# 2

## Literature review

This chapter reviews the existing literature related to the main themes of the study. It begins by exploring the fundamental concepts of green building, including its key approaches, principles, and global development trends. The chapter then narrows its focus to the Cambodian context, examining the current state of green building practices, existing initiatives, and the key barriers and challenges associated with their adoption. Subsequently, the chapter addresses the topic of affordable housing by reviewing its development, key challenges, and limitations, particularly in urban contexts. It further identifies critical research and design gaps in the integration of green building principles within the affordable housing sector, highlighting the need for context-specific solutions. These insights provide a foundation for the contributions of this study. The chapter then presents a state-of-the-art review of life cycle assessment (LCA), outlining its methodological framework and its application within the building sector. Finally, it examines LCA simplification approaches, including their methodologies, guidelines, and existing applications in the literature.

## 2.1 SIGNIFICANCE OF THE BUILDING SECTOR

The building sector, as a major component of the construction industry, is widely recognized as a key pillar of socio-economic development in many countries. Despite its importance, it is not considered an environmentally sustainable industry (Gardezi et al., 2021). Globally, the construction sector is a major consumer of materials and energy resources and a significant contributor to solid waste generation, GHG emissions, adverse health effects, environmental damage, resource depletion, and land use impacts (Allacker et al., 2013; Mirzaie, 2022). These impacts highlight the strong association between construction activities and environmental degradation, as well as the depletion of natural resources (Abd Rashid et al., 2015; Illankoon et al., 2019). Consequently, the building sector represents a critical area for reducing environmental impacts. In response, the industry has increasingly adopted innovative tools, stricter regulations, and voluntary environmental schemes. As a result, sustainability and the environmental performance of buildings have attracted growing attention in recent years.

Cambodia has established several policies and strategies to promote sustainability in the building sector and align with its national Sustainable Development Goals. One of the government's key objectives is to achieve carbon neutrality by 2050 (Ministry of Environment of Cambodia, 2021). In addition, several initiatives primarily led by the Ministry of Environment have been introduced to support this transition. According to Cambodia's Nationally Determined Contributions (NDCs), the country aims to reduce GHG emissions by 42%, from 155 MtCO<sub>2</sub>e under a business-as-usual scenario to 90.5 MtCO<sub>2</sub>e by 2030 (Ministry of Environment, 2020). The National Energy Efficiency Policy targets a reduction in energy consumption of at least 19% by 2030, including reductions of 34% in the residential sector and 25% in commercial and public buildings (National Committee on Energy Efficiency, 2022). At the same time, national energy demand is projected to double by 2030 and increase by 3.6 to 4 times by 2040, according to the Power Development Masterplan of Cambodia (Ministry of Mines and Energy, 2022). These projections highlight the need to expand renewable energy integration within the national grid and implement energy efficiency measures. Furthermore, the National Cooling Action Plan promotes the transition toward climate-friendly cooling solutions (Ministry of Environment et al., 2022). However, technical regulations for buildings particularly green building codes and energy efficiency design guidelines developed by the Ministry of Land Management, Urban Planning and Construction are still under development.

To achieve these policy targets, the building sector requires urgent transformation through the adoption of innovative, comprehensive, and practical tools. Such tools can support the design and delivery of high-quality buildings that are resource-efficient, energy-efficient, and environmentally and socially sustainable. The implementation of scientific and data-driven approaches can provide holistic guidance and enable the development of green and low-carbon buildings, ultimately contributing to the reduction of environmental impacts in the construction sector.

## 2.2 SUSTAINABILITY THROUGH GREEN BUILDING

The concept of green buildings is primarily driven by sustainability goals and is integral to sustainable building design, offering innovative approaches to constructing buildings and their associated infrastructure. Numerous definitions of green buildings exist in the literature. Widely accepted definitions from established institutions and researchers describe green buildings as structures that are environmentally responsible, ensuring efficient use of energy, water, and other resources while providing healthier living and working environments for occupants (ASHRAE, 2006; Cassidy et al., 2003; Hoffman & Henn, 2008; Robichaud & Anantatmula, 2011; US Environment Protection Agency, 2014). Alone (2020) further emphasizes that green buildings also referred to as sustainable buildings are designed, constructed, renovated, operated, or reused in a resource-efficient and environmentally responsible manner (Alone, 2020). Similarly, other definitions highlight both environmental and social dimensions, emphasizing the reduction of environmental footprints alongside the enhancement of occupant health and well-being (Gil-Ozoudeh et al., 2023; Kibert, 2016; Ragheb et al., 2016).

Although many definitions do not explicitly address the economic dimension, Liu et al. (2022) argue that green buildings can achieve higher commercial value than conventional buildings by maximizing economic and social benefits throughout their life cycle (Liu et al., 2022). Economic advantages can also arise from reduced resource consumption, particularly energy and water, as well as the use of locally available, sustainable, and recyclable materials (Desai, 2022; Issa & Kiraz, 2025). Existing literature demonstrates the significant benefits of green buildings across all sustainability dimensions. From an environmental perspective, green buildings can reduce water consumption by 20-40% and energy use by 30-50% compared to conventional buildings (Chen, 2025). Economically, overall construction costs may be reduced by approximately 280-410 USD. From a social perspective, green buildings enhance safety, accessibility for people with disabilities, access to public services, occupant well-being, and comfort (Mateus & Bragança, 2011; Yuan & Zuo, 2013). Therefore, green building principles should be increasingly integrated into contemporary and future urban development.

### 2.2.1 Approaches to achieve green building

Key approaches to achieving green buildings can be broadly categorized into technological, managerial, and behavioral/cultural dimensions (Meena et al., 2022; Zuo & Zhao, 2014).

- **Technological**

Technological approaches focus primarily on energy and materials, which are central to reducing resource consumption and improving efficiency in building design (Li, 2025; Sagar et al., 2025). The integration of renewable energy systems such as solar thermal systems, photovoltaic panels, small-scale wind turbines, and geothermal heat pumps has proven effective in reducing energy demand and associated emissions (Zuo & Zhao, 2014). These technologies also support advanced building concepts, including nearly zero-energy buildings and passive houses. In parallel,

material-related strategies play a crucial role, including reducing, reusing, and recycling construction and demolition waste (Courard et al., 2026). Advances in material technologies further enable the use of recycled and high-performance materials, contributing to improved energy efficiency and reduced embodied impacts. Consequently, embodied energy and embodied carbon are increasingly incorporated into green building assessments (Lützkendorf & Balouktsi, 2022; Saghafi & Hosseini Teshnizi, 2011).

- **Managerial**

Managerial approaches emphasize organizational and procedural aspects influencing green building development. These can be considered at three levels: project, company, and market (Faiz Musa et al., 2014; Zuo & Zhao, 2014). At the project level, effective implementation requires specialized expertise, adoption of green building assessment tools, training and education, stakeholder engagement, innovation, and coordination among project participants (Lambrechts et al., 2019; Zuo & Zhao, 2014). At the company level, strong commitment from top management is essential for integrating sustainability into project planning. The development of green specifications, product databases, and technical standards supports access to necessary resources (Lam et al., 2011). Additionally, implementing Environmental Management Systems and sustainability reporting practices enhances organizational performance (Bakkass et al., 2025; Pizzi et al., 2024).

- **Behavioral/cultural**

Behavioral and cultural approaches are also critical for advancing green building practices (Saleh et al., 2020; Wu et al., 2016; Zuo & Zhao, 2014). Raising awareness among stakeholders including government authorities, developers, designers, contractors, and end users is essential. Stakeholder perceptions and preferences vary; for example, residents may prioritize energy efficiency over other green attributes (Chau et al., 2010). User behavior and satisfaction are therefore key drivers in promoting green buildings. Similarly, contractors who incorporate green innovations during design and procurement phases can significantly contribute to industry advancement (Fu et al., 2020). Government incentives also play an important role, although overreliance on such mechanisms can occur. Social and psychological barriers remain significant challenges to adoption (Hoffman & Henn, 2008). Therefore, education and awareness-raising initiatives are crucial for encouraging broader acceptance and willingness to invest in green building features.

## 2.2.2 Principles of green building design

In addition to the approaches discussed above, design strategies are fundamental to achieving green buildings by enabling the integration of buildings with their surrounding environment while optimizing energy and resource efficiency (Issa & Kiraz, 2025). These strategies aim to enhance environmental performance and improve occupant well-being and quality of life (Arif et al., 2024; Yu et al., 2024). They are applied throughout the entire building life cycle, from site

selection and design to construction, operation, and end of life stages, with sustainability considerations embedded at each phase (Illankoon et al., 2019; Permana et al., 2025).

Green building design is guided by core principles that aim to reduce environmental impacts while enhancing human health and comfort (Chen, 2025). The literature identifies five key principles (Alone, 2020; Ragheb et al., 2016):

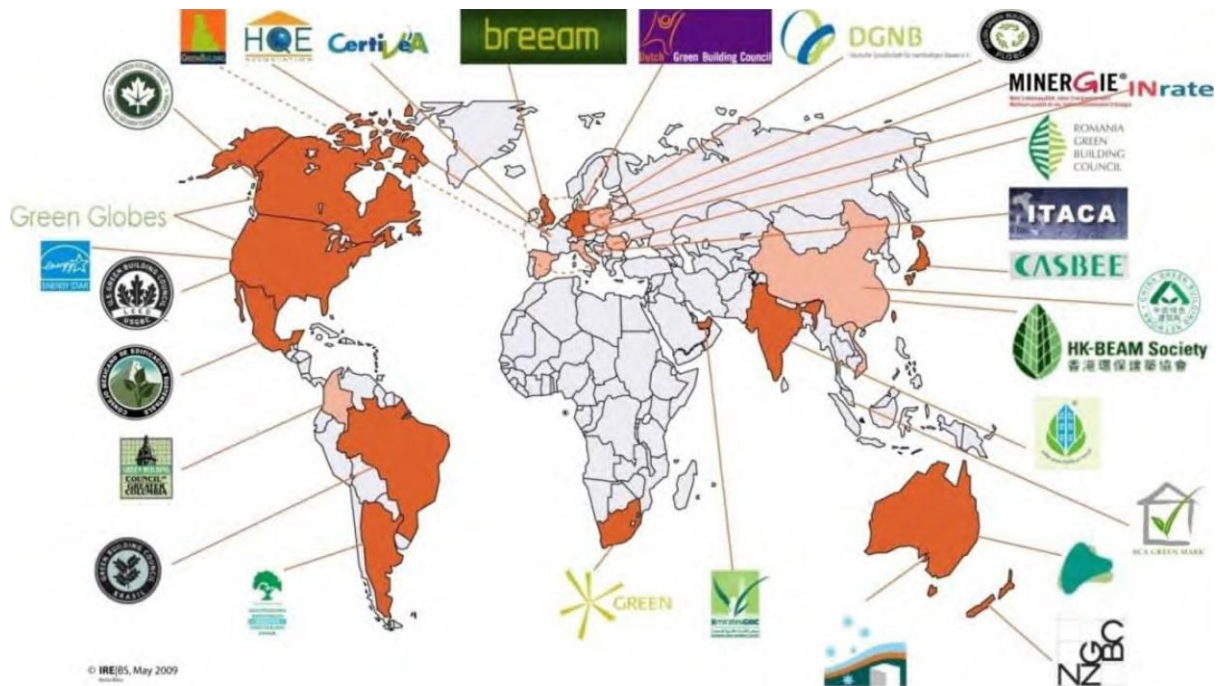
- Sustainable site planning and design
- Energy efficiency
- Water conservation and efficiency
- Indoor environmental quality
- Materials selection

These principles are implemented through various architectural and technical strategies, including passive design solutions, high-efficiency systems, renewable energy integration, water management, low-carbon materials, circular design approaches, and improvements in indoor environmental quality (Archiroots, 2025; Ecochain Technologies, 2026; Hutter Architects, 2025). However, the application of these principles is context-dependent and flexible rather than prescriptive, allowing adaptation to specific project requirements while maintaining the overarching objective of reducing environmental impacts.

### 2.2.3 Green building movement

The green building movement originated in the United States and Europe in the 1970s (Blaginin et al., 2024; Kubba, 2010; Schoch et al., 2025) and has expanded globally over the past four decades, driven by the need to mitigate environmental impacts associated with the construction industry (Durdyev & Ihtiyar, 2020). As the concept of green building has gained increasing recognition, it has stimulated the development of sustainability certification schemes to support and standardize its implementation.

Today, more than 600 sustainability certification systems for buildings and construction products are in use worldwide (Cordero et al., 2019; Vierra, 2016). Figure 2-1 illustrates selected certification schemes available globally. Prominent rating systems include DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) in Germany, LEED (Leadership in Energy and Environmental Design) in the United States, BREEAM (Building Research Establishment Environmental Assessment Method) in the United Kingdom, CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) in Japan, HQE (Haute Qualité Environnementale) in France, WELL (WELL Building Standard) in the United States, NABERS (National Australian Built Environment Rating System) in Australia, EDGE (Excellence in Design for Greater Efficiencies) developed by the International Finance Corporation (IFC), Green Star by the Green Building Council of Australia (GBCA), as well as Green Globes and Fitwel (Green Building News, 2026).



**Figure 2-1.** Worldwide sustainability certification systems (Sant & Borg, 2016).

## 2.3 BACKGROUND OF GREEN BUILDING IN CAMBODIA

Cambodia is a developing country located in Southeast Asia and has been a member of the Association of Southeast Asian Nations (ASEAN) since 1999. The construction sector is one of the leading contributors to the national economy, accounting for approximately 9-10% of GDP and ranking as the fourth largest economic sector (NCSD/Ministry of Environment of Cambodia, 2021). This sector has attracted significant foreign investment, particularly from real estate investors in China, South Korea, Japan, and other ASEAN member countries, alongside growing interest from European and American companies (Bodach, 2019; Durdyev & Ihtiyar, 2020; Keth et al., 2023). Construction activities have expanded beyond major cities such as Phnom Penh, Sihanoukville, Siem Reap, Kandal, and Koh Kong, extending to provinces along the borders with Thailand and Vietnam. In 2025, the Ministry of Land Management, Urban Planning and Construction (MLMUPC) approved 3,503 construction projects, representing a total floor area exceeding 18 million m<sup>2</sup> and an investment value of USD 7.32 billion (Khmer Times, 2025). Since the implementation of construction permitting systems, a total of 71,820 projects has been approved, covering a total land area of approximately 219 million m<sup>2</sup>, with an estimated investment of USD 87.69 billion.

Since the early 2000s, marked by rapid economic growth, Cambodia has experienced a significant expansion of its construction sector (ESCAP et al., 2024). Despite its contribution to socio-economic development, the sector is associated with increasing energy consumption and environmental impacts. Residential buildings alone accounted for approximately 35% of total energy use for heating and cooling in 2021, contributing to increased GHG emissions (Keo & Inkarojrat, 2025). Over the past 15 years, electricity consumption per capita has risen

substantially, from approximately 70 kWh in 2005 to 530 kWh in 2018 (Waibel et al., 2020). Although this level remains relatively low compared to regional averages, it is expected to grow rapidly in the coming years. Electricity demand is highly concentrated in Phnom Penh, which accounts for approximately 85% of national consumption despite representing only about 10% of the population. However, current construction laws and building codes primarily focus on structural quality and construction safety, with limited consideration of energy efficiency and sustainable or green building practices (ESCAP et al., 2024; NCSD/Ministry of Environment of Cambodia, 2021).

Although green building adoption in Cambodia is still at an early stage, the concept has attracted increasing interest from both local and international construction professionals and investors. Initial efforts include the development of certified green buildings, as well as the introduction of national guidelines and certification frameworks. Among the various international sustainability rating systems, LEED is the most widely applied in Cambodia (Durdyev & Ihtiyar, 2020). According to the Green Building Information Gateway (GBIG), fourteen facilities in Cambodia have achieved LEED certification (GBIG, 2026). Notable examples include the Vattanac Capital Tower and the Laurelton Cambodia Canteen building, as shown in Figure 2-2, left and right, respectively. Compared to neighboring countries such as Singapore, Malaysia, Thailand, and Vietnam, the adoption of green building practices in Cambodia remains limited. Nevertheless, these initiatives demonstrate a growing commitment to transitioning toward more sustainable construction practices and a greener economy.



**Figure 2-2.** Left: Vattanac Capital Tower (Knight Frank, 2026) and right: Laurelton Cambodia - Canteen building (USGBC, 2026).

### 2.3.1 Existing green building initiatives and practices

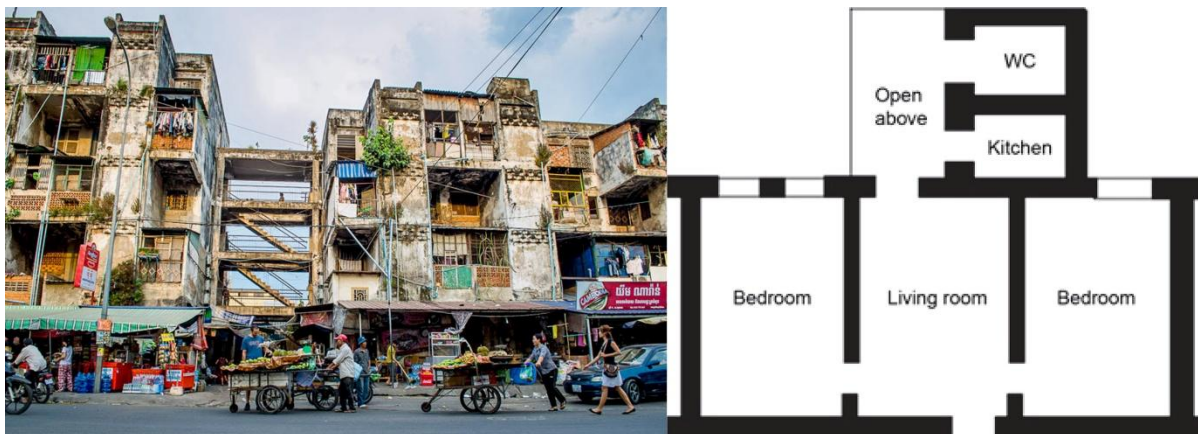
In addition to the adoption of international building assessment systems such as LEED, national initiatives toward green building have emerged in Cambodia through the development of country-specific frameworks. The National Council for Sustainable Development (NCSD) has developed a national rating system, the Cambodia Green Building Guidelines and Certification (CamGCCB), which the Ministry of Environment aims to implement nationwide to address sustainability

challenges, including rapid urbanization, public health concerns, resource depletion, and climate change (Chan, 2022; ESCAP et al., 2024; Schoch et al., 2025).

In parallel, a private-sector organization, the Cambodia Green Building Council (CamGBC), has contributed to promoting green building practices by developing guidelines and certification initiatives (CamGBC, 2026). The Global Green Growth Institute (GGGI) Cambodia also plays a significant role in enhancing readiness and supporting green building investments through programs such as the Readiness for Green Building and the Asia Low Carbon Buildings Transition projects (Ellis et al., 2013; GGGI, 2025). Furthermore, research initiatives such as the Build4People project aim to promote sustainability in urban development and improve quality of life, while raising awareness to facilitate the transition toward sustainable construction practices in Cambodia (Waibel et al., 2020).

Beyond institutional initiatives, green building principles are also reflected in traditional practices and architectural design. Cambodia has a long tradition of vernacular architecture, where buildings are designed in response to local climatic conditions. The typical rural Khmer dwelling also referred to as the traditional Cambodian wooden house is characterized by a rectangular layout elevated above ground level, with large openings for natural ventilation, and often surrounded by tropical vegetation. Construction materials typically include timber or bamboo cladding, with roofing made of clay tiles, corrugated metal sheets, or thatched palm leaves.

In addition, the New Khmer Architecture movement, which emerged in the 1950s, represents a significant milestone in Cambodian architectural development. This architectural style combines modernist principles with traditional Cambodian elements, incorporating climate-responsive design strategies derived from vernacular architecture (Bodach & Waibel, 2017; ESCAP et al., 2024; Keo & Inkarojrat, 2025). A notable example is the White Building (Figure 2-3), a multi-family residential complex designed with strong climatic adaptation features. The building consists of six blocks extending approximately 300 meters from north to south, connected by open staircases that allow natural light and ventilation through central corridors. The structure is elevated at ground level to create open communal spaces, and all apartment units are designed to enable cross-ventilation (Pen, 2015).



**Figure 2-3.** Left: *White Building before demolition in 2017 (Architecture-in-Development, 2014)* and right: *example of an apartment unit (Pen, 2015).*

Moreover, green building practices are increasingly being implemented in recent projects designed by local architectural firms. These designs predominantly adopt passive strategies, including reducing heat gain through optimized building envelopes, maximizing natural ventilation and daylighting, integrating greenery, and utilizing locally available materials. In addition, some projects demonstrate site-specific design approaches, the integration of rooftop solar photovoltaic systems for affordable electricity generation, and the use of locally sourced materials.

With regard to sustainable construction materials and techniques available in Cambodia, materials such as bamboo, recycled steel, and eco-friendly concrete incorporating fly ash and recycled aggregates have been identified and are increasingly utilized (Eurogroup Consulting, 2023). However, conventional materials including timber, brick, sand, gravel, thatch (palm leaves and straw), stone, cement, concrete, and steel remain dominant in the construction sector (Kambujaya, 2022), while the adoption of recycled and alternative materials is still limited and relatively underdeveloped.

Despite the growing interest in sustainable practices, Cambodia currently lacks comprehensive and enforceable guidelines for designing new buildings or retrofitting existing ones in an energy- and resource-efficient manner, even in the context of increasing energy consumption in the construction sector (NCSD/Ministry of Environment of Cambodia, 2021). As a result, many architects, contractors, and other construction professionals do not systematically integrate energy and resource efficiency measures, key principles of green building into their design and construction practices, often due to limited awareness, technical capacity, or regulatory incentives.

### 2.3.2 Barriers and challenges to the adoption of green building

Despite the aforementioned initiatives, the adoption of green building design and practices in Cambodia remains constrained by several persistent barriers. These challenges are primarily associated with limited awareness and understanding among stakeholders, lack of incentives and

institutional support, financial constraints, higher initial construction costs, gaps in the regulatory framework, insufficient policy implementation, and limited capacity building and technical skills (Durdyev et al., 2018; ESCAP et al., 2024; Schoch et al., 2025; Waibel, 2017). On and Techapeeraparnich (2021) further categorize these obstacles into four main groups: financial, governmental, technical, and cultural barriers (On & Techapeeraparnich, 2021). In particular, the lack of education and training among construction professionals, as well as limited access to financing for sustainability-related initiatives, remain significant constraints.

Material availability and affordability also represent critical challenges. Environmentally certified or eco-labeled materials such as low-emission paints and bricks, energy-efficient appliances, and sustainably sourced timber are still scarce and often costly in the Cambodian market (Schoch et al., 2025). Moreover, the initial investment required for green building technologies and materials is typically higher than that of conventional construction, limiting their adoption among developers, practitioners, and homeowners (Gil-Ozoudeh et al., 2023; Portnov et al., 2018). In addition, the actual performance of green buildings may vary depending on design quality and maintenance practices, which can affect the realization of expected environmental benefits.

Another important limitation lies in the reliance on conventional practices with limited analytical support from scientific data, research, or experimental validation. Research on green building adoption in Cambodia remains relatively underdeveloped (Taing et al., 2025; Waibel, 2017). Given that each country operates within a unique regulatory, economic, and cultural context, country-specific studies are essential to better understand the applicability and effectiveness of sustainable construction practices, as well as to support the development of appropriate tools and technologies (Durdyev et al., 2018; Durdyev & Ihtiyar, 2020; Karagianni et al., 2022; Long et al., 2024; Taing et al., 2023). In the absence of such localized research, developing countries like Cambodia often rely on technologies, design methods, and standards derived from developed contexts, which may not fully align with local conditions.

Addressing these barriers requires a comprehensive and context-sensitive approach that adapts existing strategies and recommendations to the Cambodian setting. Active participation and collaboration among construction professionals and relevant stakeholders are essential to advancing green building practices (Waibel, 2017). Furthermore, promoting inclusive and participatory approaches has been identified as a key factor in successfully implementing national green building rating systems (Schoch et al., 2025). The development and dissemination of clear design guidelines and recommendations can support practitioners in integrating energy- and resource-efficient strategies into building projects. Through these efforts, Cambodia can accelerate its transition toward a more sustainable built environment.

## **2.4 RESIDENTIAL SECTOR IN CAMBODIA**

Residential buildings represent a dominant component of the Cambodian construction sector, followed by commercial developments. According to the 2020 annual report of the Ministry of Land Management, Urban Planning and Construction (MLMUPC), approximately 84% of the 4,841

approved building projects were residential (NCSD/Ministry of Environment of Cambodia, 2021). With rapid urbanization and population growth, housing demand is expected to increase significantly in the coming years (ESCAP et al., 2024). Cambodia has experienced steady population growth, averaging 1.4% annually between 2014 and 2024 (The World Bank Group, 2026), while Phnom Penh continues to expand spatially and economically, further driving demand for urban housing. In recent years, numerous high-rise condominiums, gated communities, and suburban residential developments have emerged, primarily targeting middle- and upper-income groups (Waibel et al., 2020).

### 2.4.1 Residential typologies

Five major residential typologies can be identified across Cambodia. However, architectural styles and construction techniques have evolved over time under the influence of foreign design, technological advancement, and changing lifestyles. These typologies include traditional houses, link-houses (shophouses), detached houses (villas), high-density housing, and inner-city informal settlements.

Traditional houses (Figure 2-4a) are among the most common housing typologies and are considered vernacular architecture. They are primarily found in rural and remote areas. In recent years, this typology has been partially modernized, with the ground floor enclosed to provide additional living space and improved facilities. Link-houses (Figure 2-4b), introduced through Chinese shophouse typology, are common in medium- to high-density urban commercial areas. These units are typically constructed in rows, sharing walls, although some are built as detached units while maintaining a similar layout. They are also prevalent in gated communities, commonly referred to as Borey developments. High-density housing (Figure 2-4c) generally takes the form of high-rise apartment buildings located in urbanized cities such as Phnom Penh and Sihanoukville. Studio apartments are also increasingly developed to provide affordable rental options for students and young professionals. Detached houses or villas (Figure 2-4d) are typically associated with upper-income households. These are commonly located in city centers or suburban areas where larger land plots are available. Similar typologies can also be found in Borey developments, where units are often uniformly designed, including semi-detached configurations known as twin villas. Inner-city informal settlements or slums (Figure 2-4e) refer to housing areas lacking secure land tenure, structural integrity, and access to essential services. These settlements are scattered across major urban centers.



**Figure 2-4.** a: Traditional house (Seapica, 2008), b: link-house (Urban living solutions, 2024), c: high-density housing (Hotel-Phnompenh.com, 2026), d: detached house (CAM Realty Cambodia, 2026), and e: inner-city informal settlements (Khmer Times, 2023).

## 2.4.2 Overview of affordable housing projects

As in many countries, housing remains a critical issue in Cambodia, particularly in urban areas where access to affordable and adequate housing is increasingly limited for low- and middle-income households (Gerth & Sikora, 2023). Since the 1990s, the government has introduced policies to address the housing crisis, including the establishment of social housing programs. Key initiatives include the National Housing Policy (2014) and the Policy on Incentives and the Establishment of a National Program for the Development of Affordable Housing (GGGI et al., 2022).

The General Department of Housing under MLMUPC has reported four major affordable housing projects (Table 2-1) developed in collaboration with the private sector since 2014. Borey Grand Park and Arakawa Residence are located in Phnom Penh, while the other two projects are situated in Kandal Province. Arakawa Residence features an “H-shaped” design, with access provided by two centrally located elevators and staircases. The project emphasizes natural ventilation and daylighting. Safety features include fire alarms, smoke detectors, and fire-resistant doors. Its proximity approximately 6 km from the city center, provides convenient access to urban amenities.

In the Serey Mongkul Satellite City project, housing units are primarily constructed using brick, cement, and galvanized iron to improve thermal and acoustic performance. The development integrates community facilities such as a market and public green spaces. Similarly, Borey Sen Monorom Prek Taten incorporates a market, garden areas, a lake, and public transport access, using comparable construction materials.

**Table 2-1.** *Reported affordable housing development projects in Cambodia\*.*

Project	Construction land (hectare)	Number of housings (house/unit)	Number of affordable housings (house/unit)	Price (USD) per house/unit
Borey Grand Park	5.16	534	200	23,100 – 29,800
Arakawa Residence	1.36	3,164	1,928	28,500 – 31,800
Serey Mongkul Satellite City	24	2,457	2,457	25,000 – 38,888
Borey Sen Monorom Prek Taten	40.56	5,340	700	25,000 – 35,000
Total		8,331 houses 3,164 units	3,357 houses 1,928 units	

\* This table is translated from the list of affordable housing projects in the report on affordable housing and overall operations in Cambodia, written in Khmer by the General Department of Housing of MLMUPC.

Affordable housing is generally defined using affordability ratios, where housing costs should not exceed 30-40% of household income or three to four times the annual household income (GGGI

et al., 2022; Traub & Sweeting, 2020; UN-Habitat, 2016). In the Cambodian context, affordable housing typically ranges between USD 15,000 and USD 30,000 per unit and is located within 20 km of the capital (Moeng et al., 2020). Despite meeting general affordability benchmarks, housing costs in Phnom Penh accounted for approximately 31% of monthly household expenditure in 2017, significant income inequality persists (GGGI et al., 2022). It is estimated that 60-80% of the population cannot afford market-rate housing, while supply remains limited, particularly for units priced around USD 35,000.

Beyond government-supported projects, several non-market and community-driven initiatives have emerged. The Boeung Tumpun slum upgrading project (2016–2019) emphasized environmental quality, safety, and climate-responsive design (Traub & Sweeting, 2020). The Habitat Improvement for Poor Communities project (2018–2021) upgraded housing conditions in vulnerable settlements along the Tonle Sap River. The Borei Keila land-sharing project (2003–2009) focused on in-situ upgrading while maintaining proximity to employment and services. Similarly, the Stung Meanchey project (2018–2021) engaged young Cambodian architects to design housing, community spaces, and social infrastructure. These initiatives demonstrate innovative approaches to housing design, integration into urban contexts, and community upgrading. Notably, they highlight the important role of local architects and construction professionals in shaping sustainable affordable housing.

However, affordability and financial accessibility remain major challenges (Ou et al., 2025). Integrating sustainability into affordable housing design is particularly difficult due to cost constraints faced by both developers and buyers (Abbas et al., 2025; Sohaimi et al., 2025; Syed Jamaludin et al., 2020). As a result, many projects overlook long-term environmental performance, leading to inefficiencies and degradation.

Achieving sustainable affordable housing requires a holistic approach that combines financial mechanisms, material innovation, and capacity building (Muhammed et al., 2025). Despite challenges, sustainable housing offers clear benefits, including reduced operational costs, improved access to urban services, and lower environmental impact (Arman et al., 2009; GGGI et al., 2022). In Cambodia, architects and engineers play a crucial role in advancing green design and sustainability within this sector.

### **2.4.3 Research and sustainable building design gaps in the affordable housing sector**

Existing research on Cambodia's affordable housing sector has primarily focused on assessing current conditions, identifying affordability barriers, and analyzing policy gaps (Kol & Brugman, 2022; Kul et al., 2024; Menghoung et al., 2025; Traub & Sweeting, 2020). These studies often employ mixed-method approaches, with a strong emphasis on qualitative research. This reflects the importance of stakeholder perspectives in shaping housing policies and design strategies.

However, there remains a lack of research addressing context-specific definitions and characteristics of affordable housing. Such insights are essential for guiding stakeholders in

prioritizing appropriate design strategies. For example, Moeng et al. (2020) proposed prefabricated, flat-pack housing solutions using locally available materials to reduce labor and transportation costs (Moeng et al., 2020). Nevertheless, their study did not specify construction materials, detailed architectural designs, or multiple housing typologies. Similarly, Seng (2020) advocated for a Cambodian-centric framework developed through stakeholder collaboration, particularly involving local developers and construction firms. Despite these contributions, there remains a need for more detailed design guidelines, prototypes, and construction methodologies (Long et al., 2024; Moeng et al., 2020; Traub & Sweeting, 2020).

The absence of such guidance limits architects' ability to prioritize key design elements, especially in the context of climate change. Many low-income households prioritize affordability over housing quality, resulting in basic designs often delivered without professional architectural input (GGGI et al., 2022). This creates uncertainty and inconsistency in project outcomes (Adeyemi et al., 2024).

These challenges are not unique to Cambodia. Globally, integrating sustainability into affordable housing remains difficult, requiring innovative frameworks and interdisciplinary collaboration (Bruen et al., 2013; Gan et al., 2017; Karamoozian & Zhang, 2025; Reid, 2023). Establishing collaborative platforms that bring together government, private sector actors, civil society, and academia is therefore essential to address institutional fragmentation and promote sustainable building practices (Waibel, 2017).

## 2.5 LIFE CYCLE ASSESSMENT APPLICATION IN THE BUILDING INDUSTRY

Life cycle assessment (LCA) has been widely recognized as a key approach within green building practices (Al-Ghamdi et al., 2016; Faiz Musa et al., 2014; Gil-Ozoudeh et al., 2023; Illankoon et al., 2019; Wu et al., 2017; Zuo et al., 2017; Zuo & Zhao, 2014). It supports technical analysis alongside technological, managerial, and behavioral or cultural approaches discussed earlier (Sub-section 2.2.1). LCA provides a systematic framework for assessing the full range of environmental impacts associated with buildings, thereby enabling more informed decision-making during the design and construction processes (Gil-Ozoudeh et al., 2022).

From an LCA perspective, a building is treated as a system in which material and energy flows are quantified across all stages of its life cycle (Zuo & Zhao, 2014). A key advantage of LCA is its comprehensive scope: it tracks activities, resource consumption, emissions, and waste generation throughout all life cycle stages, while also enabling the evaluation of alternative solutions for environmental improvement (Abd Rashid, 2017; Utama & Gheewala, 2009; Wu et al., 2010). This contrasts with traditional approaches that often focus on a single stage or limited aspects of a building's life cycle.

From a life cycle thinking perspective, the proliferation of sustainability-related concepts in the building sector is evident. Examples include "Passive House," "Ecological Passive House," "Net

Zero Energy Building,” “CO<sub>2</sub>-Neutral Building,” “Solar Self-sufficient Building,” “Autonomous Building,” “Energy-autonomous City,” “Mixed-use Carbon-neutral Development,” “Eco-village,” “2000-Watt City,” and “Carbon Neutrality at the Neighborhood Scale” (Allacker et al., 2013). However, many of these approaches primarily emphasize energy performance, CO<sub>2</sub> emissions, and the use phase of buildings. Such a narrow focus on a single impact category or life cycle stage may lead to burden shifting, where environmental impacts are transferred to other stages or categories rather than being reduced overall (Allacker et al., 2013; Allacker & De Troyer, 2013; Ortiz et al., 2009). This highlights the growing importance of LCA in providing a more holistic assessment of environmental performance in sustainable building design.

LCA has increasingly become an integral component of building assessment processes and is incorporated into several widely recognized green building certification schemes, including BREEAM, LEED, DGNB, ÖGNI (Austrian Green Building Council), SGNI (Swiss Sustainable Building Council), TQB (Total Quality Building Assessment), BNB, BNK, Minergie-Eco, Green Globes, CASBEE, and Green Star (El khouli et al., 2015; Feng, 2020; Meex et al., 2018). Notably, certification systems such as LEED and BREEAM award additional credits for projects that perform LCA (Meex et al., 2018).

It is important to note that LCA is not a certification or labeling system; rather, it is an analytical method used to quantify and evaluate the environmental impacts of a building throughout its entire life cycle. It enables comparison between different construction options, materials, and design alternatives, and helps identify opportunities for environmental improvement (Assadiki et al., 2024; El khouli et al., 2015). The integration of LCA into research and certification schemes enhances public understanding of carbon emissions and environmental impacts, while also supporting governments and authorities in meeting regulatory requirements and environmental targets.

Despite its advancement, LCA still faces several challenges. These include methodological variability, differences in socio-economic contexts, and the inherent complexity of building systems (Feng, 2020), even though it is often considered a mature and well-established tool in the literature.

### **2.5.1 Background and basic concept of LCA**

LCA dates back to the 1960s and early 1970s, when it was first introduced and gradually developed into its current standardized form. In 1969, the Coca-Cola Company conducted a study comparing resource consumption and environmental emissions associated with glass and plastic bottles (Vigovskaya et al., 2017; Wickramaratne & Kulatunga, 2020). In 1972, Ian Boustead analyzed the total energy consumption involved in the production of various beverage containers in the United Kingdom (Vigovskaya et al., 2017). He later published the Handbook of Industrial Energy Analysis in 1979. In the early 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) played a key role in harmonizing LCA methodology, structure, and terminology, resulting in the SETAC Code of “Practice”. Building on this foundation, the

International Organization for Standardization (ISO) began developing standardized LCA frameworks in 1994, leading to the publication of the ISO 14040 series in 1997. These standards were later updated in 2006 with the release of ISO 14040 and ISO 14044, replacing earlier versions (ISO, 2006a, 2006b). Since the 1990s, LCA has been widely adopted in the building industry and is now recognized as an essential tool for evaluating environmental performance across a building's life cycle (El khouli et al., 2015; Fava et al., 2009; Ortiz et al., 2009; Vigovskaya et al., 2017).

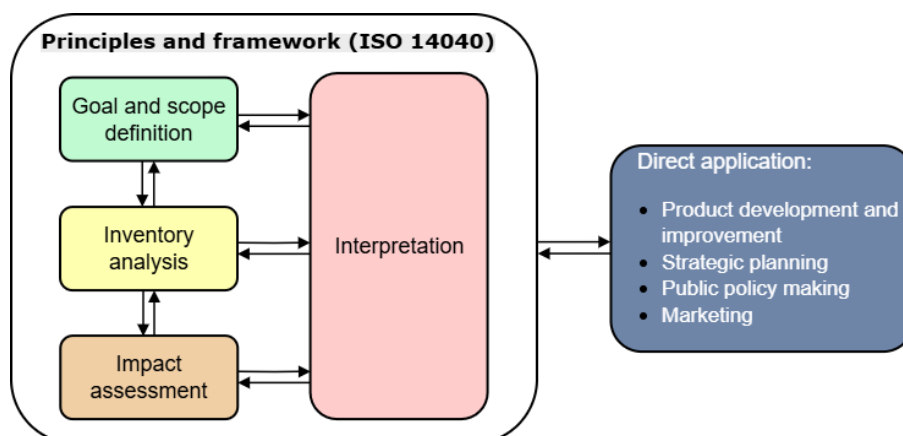
According to ISO 14040, LCA is defined as the “compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle” (ISO, 2006a). It involves the analysis of material and energy flows, where inputs (e.g., raw materials and energy consumption) and outputs (e.g., emissions, waste, and other environmental releases) are systematically assessed and linked to potential environmental impacts, such as climate change (Crawford, 2011; Simonen, 2014).

In the building sector, LCA enables construction professionals to evaluate the life cycle impacts of materials, components, systems, and services. This supports the selection of design alternatives that minimize environmental impacts over the building's lifespan (El khouli et al., 2015; Reiter, 2010). As a result, LCA is increasingly utilized by researchers, industry practitioners, policymakers, planners, and environmental organizations to inform decision-making related to sustainable development and material selection.

ISO 14040 and ISO 14044 define four interconnected phases of LCA:

- Goal and scope definition
- Life cycle inventory (LCI) analysis
- Life cycle impact assessment (LCIA)
- Interpretation

The relationship among these phases is illustrated in Figure 2-5, and each phase is described in detail in the following sections.



**Figure 2-5.** ISO LCA standards framework (ISO 2006a, 2006b).

## 1) Goal and scope definition

In the first phase, LCA practitioners define and specify the goal and scope of the study in relation to the research question, target audience, and intended application (ISO, 2006b). According to ISO 14040, this phase is essential for determining the functional unit, system boundary, and other key methodological assumptions to be reported (ISO, 2006a).

- Functional unit

The functional unit defines the function performed by the studied system and provides a reference against which all inputs and outputs are normalized. It enables the comparison of environmental impacts on a consistent basis (e.g., impacts per year of product use) and must be clearly defined and measurable (ISO, 2006b).

In the building sector, the functional unit is commonly expressed as one square meter (1 m<sup>2</sup>) of gross or total floor area, allowing comparison across different buildings on a homogeneous basis (Abd Rashid, 2017; Reiter, 2010). However, some studies refine this unit by incorporating the number of occupants to better reflect building usage. Selecting an appropriate functional unit is critical, as it must align with the study's objectives and support the comparability and benchmarking of results (Abd Rashid, 2017).

- System boundary

The system boundary defines which processes and life cycle stages are included in the LCA, in accordance with the study's goal (ISO, 2006b). It also determines the assumed lifetime of the product or building. Ideally, an LCA considers the full life cycle commonly referred to as cradle-to-grave, including all relevant unit processes.

However, in practice, this is often constrained by limitations in time, data availability, and resources (Barbhuiya & Das, 2023; Reiter, 2010). As a result, simplified system boundaries such as cradle-to-gate which exclude the use and end of life stages are frequently adopted. Therefore, it is essential to clearly define and document the selected system boundary, including all included life cycle stages and processes (Reiter, 2010).

## 2) Life cycle inventory

The life cycle inventory (LCI) phase involves compiling all relevant inputs (e.g., energy, raw materials, and ancillary materials) and outputs (e.g., products, co-products, waste, emissions to air, water, and soil) associated with the processes defined within the system boundary (Crawford, 2011; Hollberg, 2016; Islam et al., 2016; Simonen, 2014).

This phase provides a comprehensive account of elementary flows between the system and the environment across all unit processes. In the building sector, LCI includes data collection, modeling of building components, and accounting for energy, water, and material use during both construction and operation, along with data verification procedures. It is often considered one of

the most labor-intensive and time-consuming phases of LCA (Finnveden et al., 2009; Hollberg, 2016).

Two main types of data are required in this phase (Abd Rashid, 2017; EC, 2022; Goedkoop et al., 2016):

- Foreground data

Foreground data refer to project-specific data used to model the studied system. These data are typically obtained directly from stakeholders such as contractors, developers, or building owners. In the building sector, relevant data can be derived from documents such as bills of quantities and bills of materials. Although highly specific and accurate, foreground data generally represent a relatively small portion of the total data used in LCA studies (Šinik & Tošić, 2025).

- Background data

Background data refer to generic data related to processes such as energy production, transportation, and waste management (Abd Rashid, 2017). These data are typically sourced from established databases and literature and often account for the majority (up to 80%) of LCA data requirements. Commonly used databases in building LCA studies includeecoinvent, the Inventory of Carbon and Energy (ICE) database developed by the University of Bath, the U.S. LCI database, GaBi, ProBas, PSILCA, IDEMAT, BEDEC, Athena, and the Australian Life Cycle Inventory database (Assadiki et al., 2024; Bahramian & Yetilmezsoy, 2020; Reiter, 2010).

### **3) Life cycle impact assessment**

In the life cycle impact assessment (LCIA) phase, the results from the LCI are translated into potential environmental impacts (ISO, 2006a). The selection of impact categories and assessment methods is guided by the goal and scope of the study (Goedkoop et al., 2016). Most practitioners adopt established LCIA methodologies rather than developing new ones (ISO, 2006b).

According to ISO 14044, LCIA consists of mandatory and optional elements. The mandatory elements include:

- Selection of impact categories, category indicators, and characterization models

Impact categories are selected based on the study objectives. LCI results are then translated into environmental impact indicators at either midpoint or endpoint levels, such as impacts on human health, natural resources, and ecosystems (Abd Rashid, 2017; Finnveden et al., 2009). Table 2-2 summarizes the definitions of impact categories, category indicators, characterization models, and characterization factors used in the LCIA phase.

For example, for the impact category of climate change:

- Category indicator: infrared radiative forcing

- Characterization model: IPCC 100-year baseline model
- Characterization factor: Global Warming Potential (GWP)
- Unit: kg CO<sub>2</sub>-equivalent per kg of gas

**Table 2-2.** *The definitions and examples of the term used in LCIA phase.*

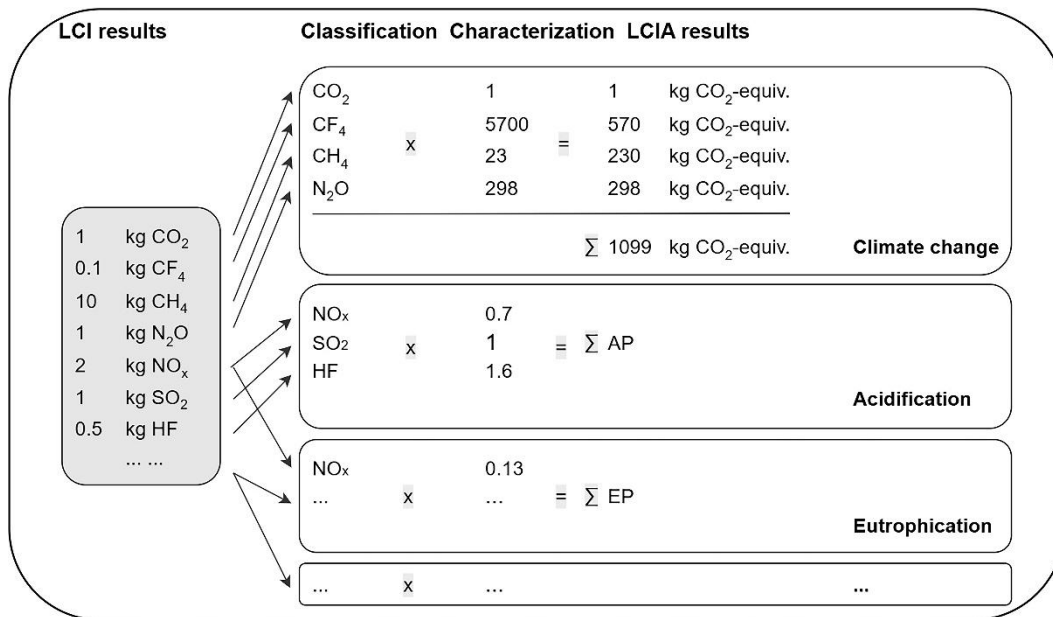
Item	Term	Definition	Examples	Reference
1	Impact categories	Class representing environmental issues of concern to which LCI results may be assigned	Climate change, Ozone depletion, Acidification	(ISO, 2006a; Life Cycle Initiative, 2008)
2	Category indicators	Quantifiable representation of an impact category	Infrared radiative forcing, Proton release	(ISO, 2006a; Life Cycle Initiative, 2008)
3	Characterization model	Mathematical model of the impact of elementary flows on a particular category indicator (provide a basis for characterization factor)	IPCC model for climate change, RAINs model for acidifying substances	(Life Cycle Initiative, 2008)
4	Characterization factor	A factor derived from a characterization model that is applied to convert the assigned LCI results to the common unit of the category indicator	Global warming potential (GWP), Acidification Potential (AP)	(ISO, 2006a; Life Cycle Initiative, 2008)

- Classification

Classification involves assigning LCI results to relevant impact categories. Flows may be allocated to single or multiple categories depending on whether they contribute to parallel or sequential environmental mechanisms (ISO, 2006b).

- Characterization

The characterization step involves quantifying indicator results by converting LCI data into a common unit and subsequently aggregating these converted values within the same impact category (ISO, 2006b). For instance, as illustrated in Figure 2-6, if the LCI results include 1 kg of CO<sub>2</sub>, 0.1 kg of CF<sub>4</sub>, 10 kg of CH<sub>4</sub>, and 1 kg of N<sub>2</sub>O, the aggregated result for the climate change impact category equals a GWP of 1099 kg CO<sub>2</sub>-equivalent.



**Figure 2-6.** Example of LCIA (data based on Hollberg, 2016).

In addition, ISO 14040 standards define optional elements:

- Normalization

Normalization expresses impact results relative to a reference value (e.g., per capita or regional totals), facilitating interpretation of their relative significance (ISO, 2006b; Life Cycle Initiative, 2008).

- Grouping

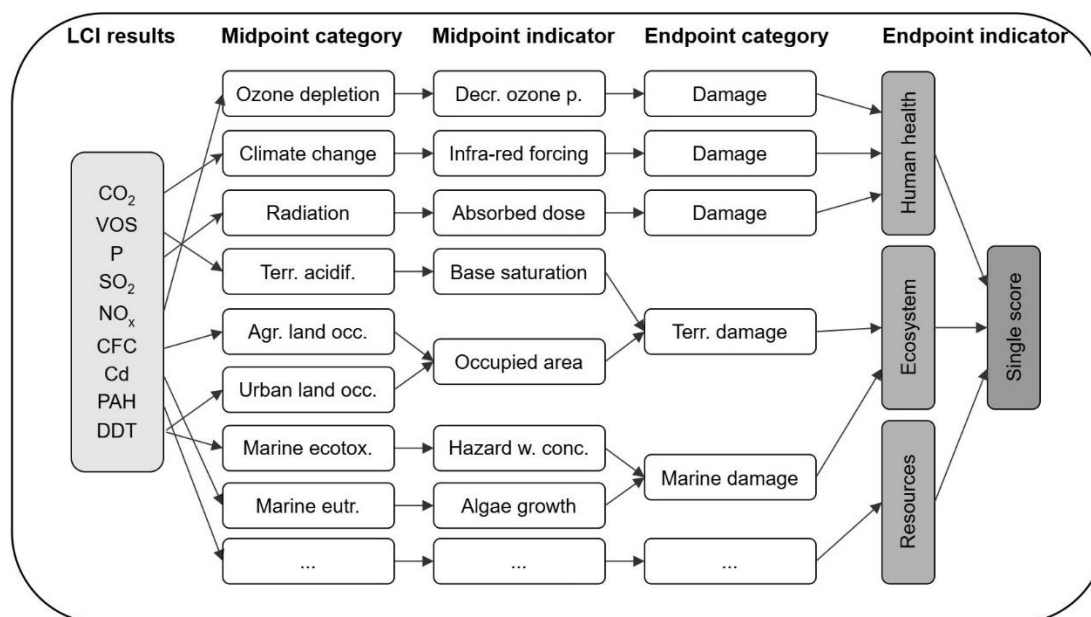
Grouping organizes impact categories into defined sets or hierarchies (e.g., global vs. local impacts or high vs. low priority) based on the study objectives (ISO, 2006b).

- Weighting

Weighting assigns relative importance to different impact categories and aggregates them into a single score. This step involves value-based judgments and may rely on methods such as monetary valuation, distance-to-target approaches, or expert panel assessments (ISO, 2006b; Life Cycle Initiative, 2008). To facilitate communication with non-experts, single-score indicators have been developed to aggregate multiple impact categories into a single value. This approach is particularly useful for architects and decision-makers, as it simplifies comparison between design alternatives (Hollberg, 2016; Meex et al., 2018).

Impact categories are often classified as midpoint (problem-oriented) or endpoint (damage-oriented). Midpoint categories (e.g., climate change) represent environmental problems, while endpoint categories translate these impacts into broader areas of concern such as human health, ecosystems, and resource depletion. As illustrated in Figure 2-7, the ReCiPe method includes 18

midpoint and 3 endpoint categories, which can be further aggregated into a single score (Goedkoop et al., 2016).



**Figure 2-7.** Example of endpoint indicators based on ReCiPe (Goedkoop et al., 2016; Hollberg, 2016).

#### 4) Interpretation

According to ISO 14040 and 14044, the interpretation phase aims to:

- Identify significant issues based on LCA results
- Evaluate completeness, sensitivity, and consistency
- Draw conclusions, explain limitations, and provide recommendations

The results are interpreted in line with the defined goal and scope of the study. This phase includes sensitivity analyses and uncertainty assessments of key inputs, outputs, and methodological assumptions to ensure the robustness and reliability of the findings (ISO, 2006b).

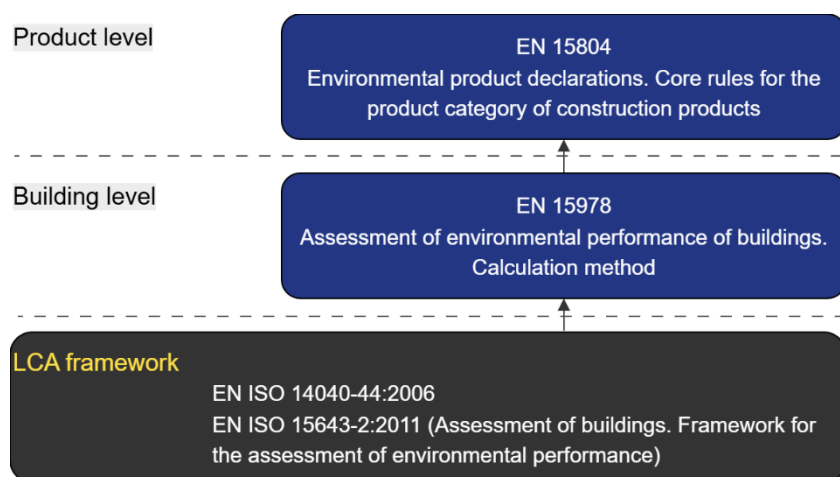
### 2.5.2 Review of LCA methodology in the building industry

LCA research in the building sector has increased significantly and is widely recognized for providing a holistic approach to comparing building designs and their associated environmental impacts. However, conducting an LCA for a complex and unique product such as a building, particularly in low-income or emerging economies, can be costly and time-consuming. It also presents challenges related to data collection, scenario development, and methodological assumptions (Abd Rashid & Yusoff, 2015; Feng, 2020; Mirzaie, 2022). As a result, the selection of appropriate standards, guidelines, methodologies, LCA tools, and databases for this research requires careful consideration. These selections should be based on their comprehensiveness,

applicability to emerging economies, and their recognition as widely used and recommended approaches in the literature.

The Technical Committee on the Sustainability of Construction Works (CEN/TC 350) developed the EN 15643:2010 standard to establish a European framework for assessing building sustainability (Hollberg, 2016). Within this framework, EN 15643:2011 (environmental performance) refers to two key standards relevant to LCA in the construction sector: EN 15978:2011, which addresses whole-building assessment, and EN 15804:2012, which focuses on construction products. These standards define general frameworks and calculation methods for product-level LCAs, Environmental Product Declarations (EPDs), and building-level LCAs.

In particular, EN 15804 plays a critical role in advancing sustainable construction by establishing consistent criteria and guidelines for evaluating the environmental performance of construction products, thereby supporting informed decision-making within the sector (Assadiki et al., 2024). Complementing these standards, the International Reference Life Cycle Data System (ILCD) Handbook developed by the Joint Research Centre (JRC) of the European Commission, provides more detailed technical guidance for LCA implementation, addressing the limitations of the relatively general ISO 14040 and ISO 14044 standards. Additionally, the EeBGuide (Wittstock et al., 2012) integrates recommendations from both European standards and the ILCD framework, offering further practical guidance for applying LCA in the building sector (Hollberg, 2016; Lasvaux et al., 2013). An overview of the relationships among current LCA standards, guidelines, and tools is illustrated in Figure 2-8.



**Figure 2-8.** Overview of current LCA standards, guidelines, and methodological frameworks used in the building sector (adapted from Mirzaie, 2022).

The environmental impact categories considered in the European Commission’s Product Environmental Footprint (PEF) method previously differed from those applied in the CML method used in the EN 15804+A1 standard, which was commonly adopted in CEN-based studies (Mirzaie, 2022). However, with the revision of EN 15804+A2, the CEN framework was aligned with the PEF methodology, adopting a consistent set of impact categories (CEN, 2019). These categories, along with their corresponding assessment models and reporting units, are presented in Table 2-3.

The earlier EN 15804:2012+A1:2013 standard defined seven core environmental impact categories: global warming potential, ozone depletion potential, photochemical ozone formation, acidification potential of terrestrial (soil) and freshwater, Eutrophication, Resource use, energy carriers / fossils, and Resource use, mineral and metals / non-fossil. In the updated EN 15804+A2, these core indicators are retained, with Eutrophication further disaggregated into terrestrial, freshwater, and marine categories, and with the addition of Water scarcity (resource use - water). The method and unit of assessment is aligned with the Environmental Footprint (EF) method (CEN, 2019; SimaPro, 2021).

In addition to the core indicators, several supplementary impact categories may be reported, including Ionizing radiation potential-human health, Respiratory inorganics / Particulate matter, Human toxicity, non-cancer, Human toxicity, cancer, Ecotoxicity freshwater (aquatic), Land use (Mirzaie et al., 2020). Human toxicity indicators represent the estimated increase in morbidity within a population, while Respiratory inorganics / Particulate matter quantifies the incidence of disease associated with emissions of fine particulate matter (PM2.5).

It should be noted that not all impact assessment methods exhibit the same level of robustness. Accordingly, the PEF Category Rules (PEFCR) guidance recommends that certain toxicity-related indicators namely Freshwater ecotoxicity, Human toxicity (cancer), and Human toxicity (non-cancer) be included in characterization results but excluded from hotspot analysis and benchmarking (or communicated separately as “other impact results”) (Mirzaie, 2022). This recommendation was considered provisional, pending further methodological refinement following the PEF transition phase.

**Table 2-3.** EF 3.0 midpoint impact categories with their assessment models and unit.

<b>Impact category</b>	<b>Assessment model</b>	<b>Unit</b>
Climate change	Bern model - Global warming potential over a 100-year time horizon based on IPCC	kgCO <sub>2</sub> eq
Ozone depletion	EDIP model based on the ODPs of the World Meteorological Organization (WMO) over an infinite time horizon	kg CFC11 eq
Ionizing radiation	Human Health effect model	kBq U <sup>235</sup> eq
Photochemical ozone formation	LOTOS-EUROS model	kg NMVOC eq
Particulate matter	UNEP PM model	disease inc.
Human toxicity, non-cancer	USEtox model	CTUh
Human toxicity, cancer	USEtox model	CTUh
Acidification	Accumulated Exceedance model	mol H <sup>+</sup> eq
Eutrophication, freshwater	EUTREND model	kg P eq
Eutrophication, marine	EUTREND model	kg N eq
Eutrophication, terrestrial	Accumulated Exceedance model	mol N eq
Ecotoxicity, freshwater	USEtox model	CTUe
Land use	Soil quality index based on LANCA model	Pt

Water use	UNEP Available Water REmaining (AWARE) model	m <sup>3</sup> depriv.
Resource use, fossils	CML2002 model	MJ
Resource use, minerals and metals	CML2002 model	kg Sb eq
CFC-1= Trichlorofluoromethane, also called freon-11 or R-11, is a chlorofluorocarbon CTUe = Comparative Toxic Unit for ecosystems CTUh = Comparative Toxic Unit for humans PM2.5 = Particulate Matter with a diameter of 2.5 µm or less NMVOC = Non-Methane Volatile Organic Compounds Sb = Antimony		

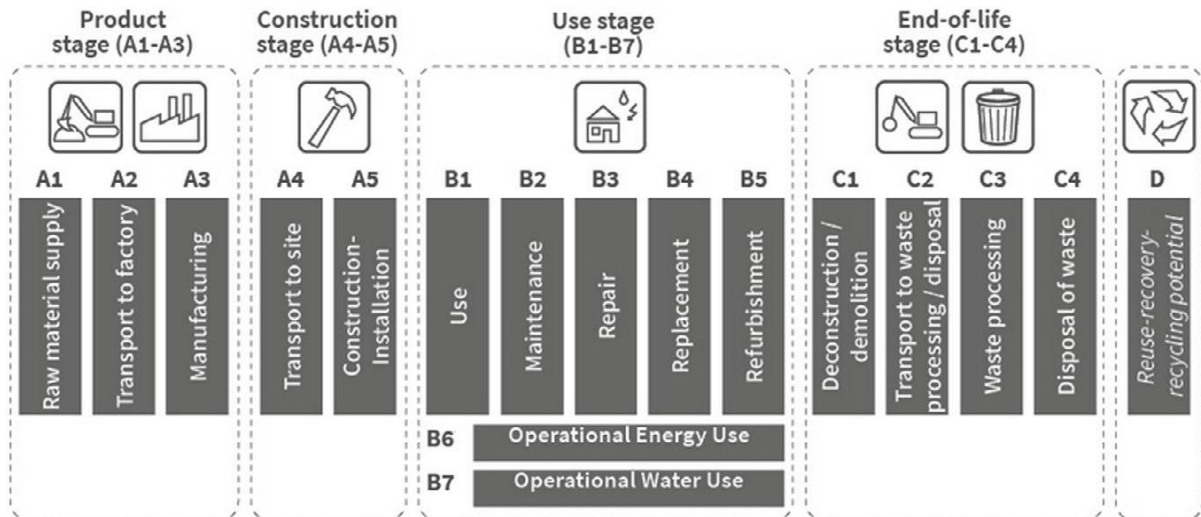
LCA research has predominantly focused on disciplines such as engineering, environmental sciences, ecology, and construction and building technology, with increasing attention in recent years to topics such as building envelopes and living walls, as indicated by citation trends (Assadiki et al., 2024). Methodologically, LCA can be conducted using three main approaches: process-based (bottom-up), input-output (IO) (top-down), and hybrid methods that combine both approaches (Abd Rashid, 2017). Among these, the process-based method is the most widely applied in building LCA studies due to its ability to provide detailed, product-level information, enabling comparison between specific construction alternatives (Monteiro et al., 2016).

The process-based approach, which underpins the CEN standards for building LCA (Moncaster et al., 2018), defines system boundaries and quantifies impacts by accounting for the individual materials and processes contributing to a functional unit, such as a building (Mirzaie, 2022; Simonen, 2014). Despite its specificity, this approach is time-intensive and subject to systematic truncation errors, as it excludes indirectly induced impacts beyond the defined system boundary (Lenzen & Treloar, 2002; Zhang et al., 2019). In contrast, the input-output (IO) method adopts a top-down perspective, using sectoral economic data and energy intensity information to estimate environmental impacts across entire industrial supply chains at the macro level (Seo et al., 2016). While this approach benefits from broader system boundaries and typically yields higher and more comprehensive impact estimates, it is associated with uncertainties due to aggregation errors, which limit its ability to distinguish between processes within the same sector (Crawford, 2011; Moncaster et al., 2019; Röck et al., 2020).

To address the limitations of both approaches, hybrid LCA methods have been developed, integrating process-based and IO data. These methods enhance system completeness and reduce truncation errors, often resulting in higher estimates of embodied impacts compared to process-based analyses alone (Stephan & Crawford, 2014).

Due to inconsistencies in the definition of system boundaries across existing LCA tools (Feng et al., 2022; Hollberg, 2016), the building LCA standards EN 15804 and EN 15978 establish a harmonized framework by dividing the building life cycle into five stages (Figure 2-9). These stages and their corresponding modules are summarized as follows:

- Product stage (A1-A3): Includes raw material supply, transport, and manufacturing of construction materials and products, encompassing all upstream processes such as energy provision and packaging. Assessments limited to this stage are referred to as cradle-to-gate.
- Construction process stage (A4-A5): Covers transport of materials to the construction site, on-site activities, and installation processes, as well as waste generated during construction.
- Use stage (B1-B7): Encompasses use, maintenance, repair, replacement of the building-integrated construction products and refurbishment activities, in addition to operational energy and water use. Where, B1 to B5 modules are related to the building fabric and components and B6 and B7 are related to the operation of the building as a whole.
- End of life stage (C1-C4): Includes de-construction or demolition, transport, waste processing, and final disposal.
- Benefits and loads beyond the system boundary (D): Accounts for potential benefits and loads from reuse, recovery, and recycling beyond the defined system boundary.



**Figure 2-9.** Life cycle stages of a building according to EN 15978 (Assadiki et al., 2024).

Choosing appropriate LCA software is also an important aspect that requires careful consideration. The capability of an LCA software largely depends on the quality and comprehensiveness of its embedded databases (Mirzaie, 2022). For conducting a complete LCA that involves intensive data processing and analysis, comprehensive tools such as SimaPro and OpenLCA, equipped with up-to-date, accurate, generic, and relevant databases, are commonly recommended (Herrmann & Moltesen, 2015; Mirzaie, 2022).

SimaPro is particularly suitable for assessing a wide range of environmental impacts of buildings across their entire life cycle and is considered one of the most widely used software–database combinations in the building LCA field (Emami et al., 2019; Gu et al., 2024). The software offers flexibility in modelling, includes a wide range of databases, and allows users to modify input data to better reflect regional conditions that may not be explicitly represented in default datasets. This

flexibility enables the development of detailed building models that are consistent with different methodological approaches.

A review by Bahramian and Yetilmezsoy (2020), covering two decades of LCA studies in the building sector, confirmed that SimaPro has been the most commonly used software in computer-aided LCA applications (Bahramian & Yetilmezsoy, 2020). Among the databases integrated within SimaPro, ecoinvent is widely recognized as the most frequently used database in building-related LCA studies. This is primarily due to its status as the largest transparent unit-process life cycle inventory database, characterized by high data quality, completeness, and transparency (Martínez-Rocamora et al., 2016; Wernet et al., 2016).

Ecoinvent provides comprehensive and high-quality life cycle inventory and impact assessment datasets, covering a broad range of processes and materials (ecoinvent, 2026). A review by Talpur et al. (2023) further confirmed that SimaPro is among the most commonly used tools for conducting LCA of construction materials in South Asian countries, where the ecoinvent database is consistently applied (Talpur et al., 2023). These tools and databases have also been widely applied in building LCA studies across Asia, including residential buildings in India (Pinky et al., 2012), Egypt (Ali et al., 2015), Malaysia (Abd Rashid et al., 2017), institutional buildings in Pakistan (Talpur et al., 2022), and prefabricated wooden houses in Vietnam (Tang et al., 2025).

### 2.5.3 Literature highlighting LCA application in Cambodia and green building design

Despite the advancement of LCA research in many parts of the world, evidence on its application in developing countries remains limited (Amarasinghe et al., 2020), particularly in Cambodia. LCA is still relatively unfamiliar to the public, and its implementation at the national level remains very limited.

Over the past decade, approximately ten scientific publications related to LCA have been identified in Cambodia across various sectors, including cooking fuels, photovoltaic lighting systems, municipal solid waste management, cement production, hydropower generation, food production systems, residential building, and industrial textile boilers (Aberilla et al., 2020; Chea et al., 2022; Chhun et al., 2021; Durlinger et al., 2012; Hang et al., 2023; Hor et al., 2021; Long et al., 2025; Poeung et al., 2024; Srun, 2015; Yim & Toshiya, 2022). Notably, only one study has applied LCA to the building sector, which forms part of this doctoral research. Wiloso et al. (2019) further confirmed that Cambodia, along with Brunei, Myanmar, and Lao PDR, plays only a minor role in LCA research within Southeast Asia (Wiloso et al., 2019). Moreover, LCA applications in the building sector remain largely absent in Cambodia.

Several studies and reviews strongly recommend that developing and low-income countries adopt LCA methodologies across different sectors, particularly in the building industry, due to its significant environmental impacts that cannot be overlooked (Nawarathna et al., 2021; Ramjeawon, 2012). However, this transition remains constrained by limited data availability, methodological capacity, and research experience, resulting in a lack of comparative studies

between developed and developing countries (Amarasinghe et al., 2020). This also leads to a shortage of benchmarks for countries with similar socio-economic contexts.

Recent studies from Southeast Asia demonstrate the potential of LCA in supporting green building and low-carbon development strategies. For example, in Vietnam, Le et al. (2021) assessed CO<sub>2</sub> emissions of a high-rise office building under two design scenarios using different brick and glass types. The study found that the “greener” material scenario reduced emissions by approximately 38%, highlighting the environmental benefits of sustainable design choices (Le et al., 2021). In Malaysia, Jia Wen et al. (2015) compared industrialized building systems (IBS) with conventional cast-in-situ construction in low-rise apartment buildings (Jia Wen et al., 2015). Their results showed that IBS significantly reduced embodied energy and GWP, supporting its role in low-carbon construction development. In Thailand, Kofoworola and Gheewala (2008) applied LCA to a commercial office building and demonstrated that simple, no-cost energy conservation measures such as increasing indoor temperature set-points by 2°C and implementing load shedding could reduce annual GWP by approximately 4% (Kofoworola & Gheewala, 2008).

In the Philippines, Salzer et al. (2017) compared conventional and alternative construction methods for social housing using LCA (Salzer et al., 2017). Their findings indicated that alternative systems such as soil-cement blocks, cement-bamboo frames, and coconut board-based housing could reduce life cycle GWP by approximately 35%, 74%, and 83%, respectively. These results emphasize the strong potential of alternative construction technologies for reducing environmental impacts in the housing sector, particularly in developing contexts.

Overall, these studies highlight that LCA applications in emerging economies should incorporate context-specific and realistic scenarios to ensure meaningful and applicable results. Based on the reviewed literature, several research gaps can be identified. First, environmental impact assessment should extend beyond GWP and embodied energy to include a broader range of impact categories. Second, decarbonization strategies should adopt more integrated approaches that consider both material and energy efficiency simultaneously. Finally, future studies should explore multiple design scenarios rather than limiting comparisons to only two or three alternatives, to better support comprehensive decision-making for low-carbon and green building development.

## 2.6 SIMPLIFICATION OF BUILDING LCA STUDY

In the context of applying LCA in building design, conducting a full LCA is often associated with several challenges, including being highly time-consuming, resource-intensive, and not always aligned with the needs of design teams. It is also frequently constrained by limited data availability and may not be fully completed in practice (Gradin & Björklund, 2021; Hollberg, 2016; Lasvaux et al., 2013; Wittstock et al., 2012).

As a result, building professionals and LCA practitioners continue to explore more integrated, efficient, and user-friendly approaches for incorporating LCA into the design and construction

process (Bueno & Fabricio, 2018). To address these challenges, simplified LCA methodologies have been developed and increasingly adopted, particularly in the early design stages (Gradin & Björklund, 2021; Hochschorner & Finnveden, 2003; Hollberg & Ruth, 2016; Soust-Verdaguer et al., 2016).

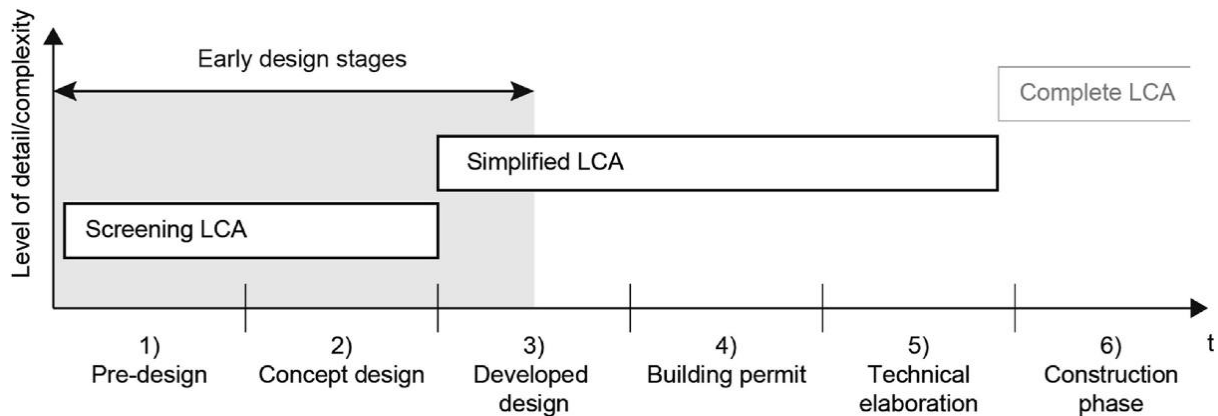
Architects and planning professionals increasingly recognize the value of LCA in supporting design decision-making, particularly in material selection for specific development schemes (El khouli et al., 2015; Mateus & Bragança, 2011). Since decisions made at early design stages have a critical influence on a building's overall environmental performance, LCA can help designers identify and prioritize decisions that have the most significant environmental implications (Basbagill et al., 2013; Hollberg, 2016). Therefore, LCA should ideally be applied as early as possible in the design process to evaluate alternative design solutions and support optimal decisions based on the building's full life cycle impacts.

### **2.6.1 Recommendations and guidelines for LCA simplification**

Simplified LCA approaches are particularly important in the building sector due to the complexity and diversity of materials and components involved (Abd Rashid & Yusoff, 2015; Hollberg, 2016). A wide range of literature has proposed various simplification techniques, tools, and strategies for building-related LCA (Bonnet et al., 2014; Hollberg & Ruth, 2016; Kjaer Zimmermann et al., 2019; Lasvaux et al., 2013; Lewandowska et al., 2015; Soust-Verdaguer et al., 2016; Zabalza Bribián et al., 2009). Beyond serving as decision-support tools for design alternatives, simplified LCA also contributes to broader adoption of LCA in practice by making it more accessible and applicable across different contexts (Beemsterboer, 2019).

The EeBGuide distinguishes three levels of LCA depending on the degree of simplification: screening LCA, simplified LCA, and complete LCA (Wittstock et al., 2012). Screening LCA is typically applied in the pre-design or conceptual design phase, while simplified LCA is used in more developed design stages (Budig et al., 2021). In contrast, complete LCA requires detailed and high-resolution input data, covering both embodied and operational impacts throughout the entire life cycle.

Given the high level of uncertainty and limited design information available in early project stages (Meex et al., 2018), complete LCA is often less practical, whereas simplified approaches are more suitable and feasible. The level of detail in each LCA type depends on the available design information, particularly material specifications, as illustrated in Figure 2-10. In addition, several building certification schemes already incorporate simplified or screening LCA approaches, such as DGNB, BNB, HQE, BREEAM, and Verde, while schemes such as Minergie-ECO and LEED primarily apply screening LCA. These practices support the integration of simplified LCA into broader green building assessment frameworks.



**Figure 2-10.** Relation between design stages and simplifications in LCA (Meex et al., 2018).

### 1) Environmental data quality

Environmental data are time- and location-dependent and therefore only valid under specific geographic and temporal conditions. To ensure data reliability, the origin and consistency of datasets must be clearly documented. In early design stages, the geographical origin of materials is often unknown; therefore, while region-specific data may be recommended, it is not always mandatory.

To maintain consistency, data should preferably be sourced from a single database to ensure that all building components are based on comparable methodological assumptions (Häfliger et al., 2017; Wittstock et al., 2012). Building material data can be classified as specific, average, or generic. Although specific data are the most accurate, they are often unavailable during the early design stages. Therefore, generic data are typically used for screening LCA, while average (or generic) data are applied in simplified LCA, and more specific data are recommended for complete LCA, in accordance with EN 15978 and the EeBGuide recommendations summarized in Table 2-4 (Meex et al., 2018).

**Table 2-4.** Three level of LCA: screening, simplified, and complete LCA recommendation by EeBGuide.

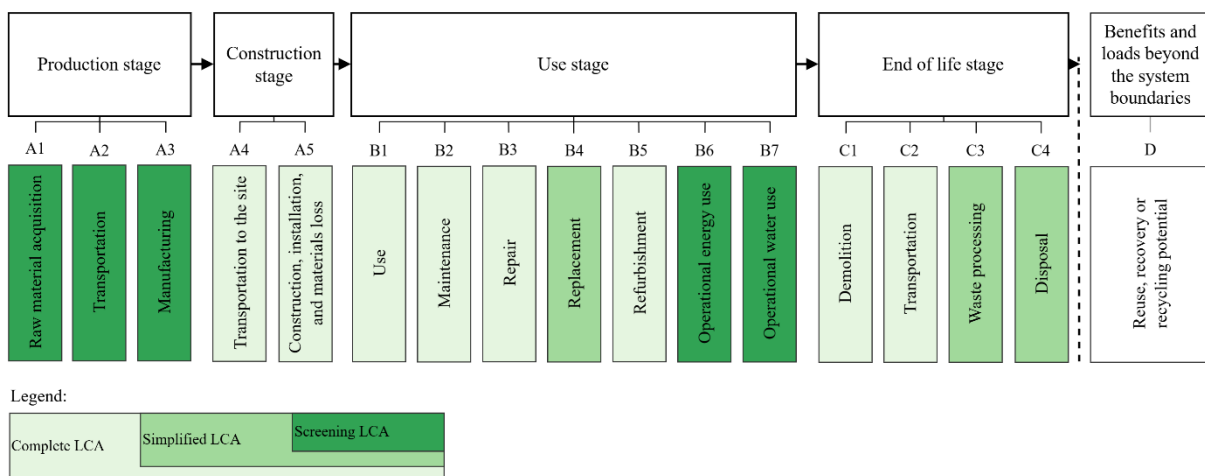
	<b>Screening LCA</b>	<b>Simplified LCA</b>	<b>Complete LCA</b>
<b>Type of data</b>	Generic LCA data	Generic or average LCA data	Specific LCA data (EPDs)
<b>Mandatory life cycle modules</b>	A1-A3, B6, B7	A1-A3, B4, B6, B7, C3, C4, D	A1-A3, A4, A5, B1, B2, B3, B4, B5, B6, B7, C1, C2, C3, C4, D
<b>Mandatory building components to be included</b>	Roof, load-bearing structures, building envelope including windows, floor slabs, foundation, floor finishes/coverings	Roof, load-bearing structures, building envelope including windows, floor slabs, foundation, floor finishes/coverings	Roof, load-bearing structures, building envelope including windows, floor slabs, foundation, floor finishes/coverings, wall finishes/coatings,

			doors, building services including heating, cooling, lighting, escalators/lifts, water system
<b>Number of impact indicators employed</b>	At least 1 or two indicators	Reduced indicator set	A comprehensive set, e.g. list from EN 15978 or list from ILC Handbook

## 2) Life cycle modules

A key aspect of LCA simplification is the definition of system boundaries through the selection of life cycle modules. For transparency, all included modules must be clearly declared. According to the EeBGuide, screening LCA typically includes modules A1–A3, B6, and B7, as summarized in Table 2-4 and illustrated in Figure 2-11. The product stage (A1–A3) generally contributes the largest share of embodied impacts and is therefore essential. When combined with operational energy use (B6), these modules account for approximately 70–90% of total life cycle impacts in residential buildings (Cuéllar-Franca & Azapagic, 2012; El khouli et al., 2015; Kellenberger & Althaus, 2009). Moreover, these modules are well documented in Environmental Product Declarations (EPDs) and databases, making them suitable as a minimum system boundary for screening LCA.

For simplified LCA, additional modules such as A1–A3, B4, B6, B7, C3, and C4 are included, while module D is considered optional to provide a more comprehensive assessment. Although modelling beyond the system boundary (module D) can introduce methodological complexity (Wastiels et al., 2013), it may significantly influence results particularly for bio-based materials and should therefore be included where relevant (Häfliger et al., 2017).



**Figure 2-11.** Life cycle stages to be considered (based on EN 15978)

### **3) Building components to be included**

The EeBGuide also provides guidance on the level of building components to be included during early design stages. For screening and simplified LCA, the minimum scope should include the building envelope (external walls, windows, roof, and floor slabs), floor finishes, foundations, and primary structural elements. These components are responsible for approximately 76% of embodied environmental impacts on average (El khouli et al., 2015).

For complete LCA, additional elements such as interior finishes, doors, and building services (e.g., heating, cooling, lighting, lifts, and water systems) are included. However, minor elements such as staircases, cables, and door handles may be excluded in certain certification systems, such as those applied by the DGNB (German Sustainable Building Council, 2026).

### **4) Environmental indicators**

The EeBGuide provides limited guidance on the number of indicators to be used in screening LCA. It suggests that screening studies may focus on one or several indicators, with a minimum inclusion of PENRT (total non-renewable primary energy) and, where relevant, GWP (global warming potential) and PERT (total renewable primary energy) (Wittstock et al., 2012).

While a single indicator may be suitable for specific applications, it is insufficient for comprehensive building assessment, as it may lead to burden shifting and incomplete conclusions. For instance, some wood-based materials may show negative GWP values, which can be misleading if other environmental impacts are not considered.

Current European standards, including EN 15804 and EN 15978, define a broader set of environmental indicators for building assessment, although national requirements may differ (Meex et al., 2018). Based on the EeBGuide, screening LCA should at least include PENRT and GWP. For simplified LCA, a more comprehensive set of indicators is recommended, including impact categories such as GWP, EP (eutrophication potential), AP (acidification potential), ODP (ozone depletion potential), POCP (photochemical ozone creation potential), and ADP (abiotic depletion potential), as well as input-related indicators such as PET (total primary energy) and PENRT. These indicators represent minimum requirements that may be expanded in line with evolving standards and regulatory frameworks.

#### **2.6.2 Existing literature on simplification of LCA**

Despite the growing attention given to simplified LCA methods, their application within the construction sector remains relatively limited (Zhou et al., 2023). In particular, only a small number of studies have systematically compared the deviations in results across different levels of LCA detail. Bonnet et al. (2014) compared simplified and complete LCA results for a building and reported a maximum deviation of approximately 20% (Bonnet et al., 2014). Similarly, Lasvaux et al. (2013) identified a deviation of around 30% in GWP results between simplified and complete LCA approaches (Lasvaux et al., 2013). In another study, a comparison between

screening and simplified LCA for a townhouse showed a much smaller deviation of approximately 3% for GWP results (Long et al., 2025). Beyond the construction sector, Hur et al. (2005) evaluated different screening LCA methods for consumer products such as mobile phones and vacuum cleaners, reporting deviations of up to 60% when compared to complete LCA results (Hur et al., 2005).

Due to limitations in the EeBGuide, which does not explicitly define acceptable accuracy ranges relative to complete LCA, it is generally assumed based on existing literature that maximum deviations of approximately 30% for screening LCA and 20% for simplified LCA are acceptable (Meex et al., 2018). Furthermore, many previous studies have primarily focused on the development of simplified LCA models and the evaluation of their accuracy, while often neglecting in-depth analysis and interpretation of the resulting outcomes (Zhou et al., 2023). Therefore, additional comparative studies between simplified and complete LCA approaches for buildings are needed to further validate and refine these deviation benchmarks.

Another limitation of the EeBGuide is the lack of specification regarding the choice of environmental indicators. The use of multiple indicators, while comprehensive, can be difficult to interpret for non-expert users such as architects and decision-makers. In this context, the use of a single-score indicator is recommended, as it facilitates clearer communication and may promote wider adoption of LCA in practice (Hollberg, 2016; Meex et al., 2018).

## 2.7 CHAPTER CONCLUSION

This literature review has been conducted based on four main thematic areas: green building design, affordable housing, LCA of buildings, and LCA simplification. These themes are closely aligned with the problem statement and research objectives outlined in the Introduction chapter.

The review indicates that the building sector represents a critical domain for reducing environmental impacts and advancing sustainability, particularly through the adoption of green building design strategies in the residential sector. Although research and practical applications of green building have progressed significantly at the global level, their implementation in the Cambodian construction sector remains limited and faces multiple barriers, especially in the context of developing green affordable housing. Existing literature highlights that affordable housing development is already constrained by financial, institutional, and technical challenges. At the same time, green building design and practices encounter additional limitations, including lack of technical capacity, policy support, and contextual adaptation. Consequently, there is a clear research gap in integrating green building principles into affordable housing, particularly in terms of defining context-specific design strategies, construction techniques, and performance criteria.

Among the recognized approaches to green building design, LCA has emerged as a comprehensive and effective method. However, similar to the broader limitations in green building practices, the application of LCA in the Cambodian building sector remains largely absent. This is despite its strong potential to systematically evaluate environmental impacts across the entire life cycle of

buildings, track resource flows, and support decision-making for decarbonization and environmental improvement. Although LCA methodologies have reached a relatively advanced stage globally, several critical gaps persist in developing regions such as Cambodia and Southeast Asia. These include the lack of benchmark environmental performance data, limited application across diverse environmental indicators, and insufficient integration of LCA into building design strategies, particularly in relation to material optimization and operational energy performance.

Furthermore, LCA simplification approaches, including screening and simplified LCA, offer practical tools to support early-stage design decision-making. Despite the limited number of studies comparing simplified LCAs and complete LCA results, the adoption of simplified approaches is particularly relevant in emerging contexts such as Cambodia, where LCA implementation is still in its early stages. These approaches can facilitate the use of LCA by architects and engineers and support its integration into the building design process.

In light of these findings, there is a strong justification for further research on the application of LCA in the building sector, particularly for the development of green affordable housing in Cambodia. Such research can contribute to bridging existing knowledge gaps and support the transition toward more sustainable and low-carbon building practices, both locally and in similar developing contexts.

# 3

## Methodology

This chapter provides a comprehensive overview of the research methodology employed throughout the study. It outlines the specific tasks and methods undertaken at each phase of the research process to achieve the stated objectives and address the research questions presented in the Introduction chapter. The selection of each method is critically examined, and a rationale is provided to justify its appropriateness within the context of this study.

### 3.1 GLOBAL RESEARCH METHODS

The focus of this research is to identify green building strategies that reduce life cycle environmental impacts and to introduce simplified LCA tools for the design of green affordable housing in Cambodia. The research objectives are achieved through a structured methodology encompassing data collection, analysis, and interpretation. The research design was developed based on an initial literature review of academic publications, followed by the formulation of research questions that guided the main research tasks. Data collection and analysis were conducted using survey methods and LCA frameworks, with final interpretation integrating all findings. Figure 3-1 illustrates the relationships between the different research phases and methods. Detailed explanations of each method are provided in the following sections.

Limited in-depth studies exist that investigate contextual aspects of how buildings are designed, constructed, and operated within specific local settings. These processes are not driven solely by technical guidelines but are also shaped by socio-technical factors in practice (De Carli et al., 2025; Lowe et al., 2018). Building projects involve multiple stakeholders who participate in complex processes from the design stage through to construction completion. Therefore, close engagement such as interviews and social interactions enables a deeper understanding of the local construction sector from a multi-stakeholder perspective, particularly regarding the integration of green building strategies and affordable housing design.

LCA was selected as a primary methodological approach due to its scientific robustness and its capacity to evaluate the environmental performance of buildings. It also allows for the exploration of alternative strategies to reduce life cycle impacts and associated emissions. LCA serves as a critical tool for bridging green building strategies with affordable housing design, making it highly relevant to this research. In the context of developing and low-income countries in Southeast Asia, including Cambodia, building LCA studies remain limited, as discussed in the literature review. Conducting one of the first LCA-based building studies in this context further supports the methodological choice. Additionally, the introduction of simplified LCA approaches offers practical value for architects and engineers, enabling wider adoption in real-world design processes.

This research therefore integrates building design strategies derived from stakeholder perspectives with life cycle analysis of two residential case studies. The study also evaluates improvement scenarios and introduces simplified LCA tools to support decision-making.

To enhance reliability and reduce bias, diverse and complementary data sources were employed (data triangulation). This approach enabled a comprehensive understanding of contextual design practices, stakeholder perspectives, technology adoption, and environmental performance of existing buildings. Given the complexity of the research objectives, a pragmatic mixed-methods approach was adopted, combining qualitative methods (semi-structured interviews) and quantitative methods (LCA) (Ahmed & Pereira, 2024; Ambrose et al., 2017; Creswell & Plano Clark, 2011; Mirzaie, 2022). Recent studies in Cambodia, such as Taing (2024) and Keth (2025),

have similarly employed mixed-methods approaches to address technological advancement in the construction sector (Keth, 2025; Taing, 2024). Keth (2025) further highlights that this approach is particularly suitable in contexts where limited documentation exists and direct field engagement is required (Keth, 2025).

Although qualitative and quantitative methods are grounded in different philosophical traditions, their integration allows for a more comprehensive analysis. This combination enables the exploration of green building and affordable housing integration from multiple perspectives, while also quantitatively assessing environmental performance through LCA. No single method can fully capture the complexity addressed in this research (Gibson, 2017; Mertens, 2010). The mixed-methods design adopted in this study follows a convergent parallel design, in which qualitative and quantitative data are collected and analyzed independently but concurrently, and then integrated during the interpretation phase (Creswell & Plano Clark, 2011; Edmonds & Kennedy, 2017). For example, the LCA of the first case study and the survey were conducted simultaneously, while comparative LCA analyses were performed sequentially afterward. All data sources were given equal priority during the final interpretation stage, ensuring a balanced and comprehensive conclusion.

Additional methods, including on-site measurements and consultations with building owners, engineers, and material suppliers, were also considered. While not central to the research design, these methods were used to supplement data collection. On-site measurements were particularly necessary due to the absence of technical documentation and bills of quantities for the first case study. Discussions with the building owner provided further clarification and completeness of data. Furthermore, remote consultations with construction professionals and suppliers were conducted to obtain material specifications and properties required for LCA modeling. These supporting methods were essential in addressing data gaps and were implemented with appropriate permissions, in line with recommendations from existing literature.

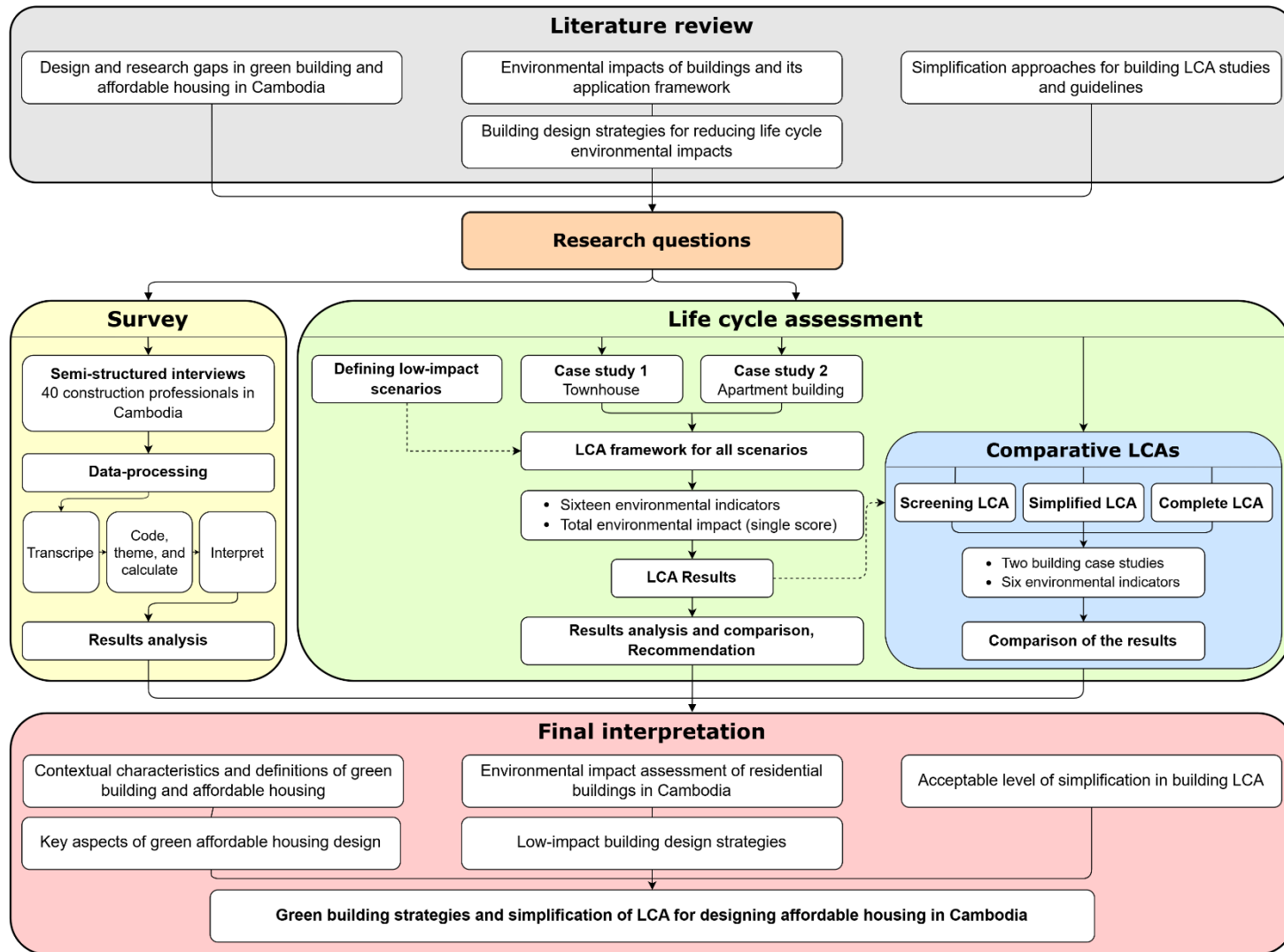


Figure 3-1. Research methodology design.

## 3.2 LITERATURE REVIEW

The literature review constitutes the first methodological step of this research and aims to provide critical insight into the key themes relevant to the research focus. It supports the refinement of research questions, hypotheses, and the identification of gaps to be addressed. This comprehensive review is directly linked to data collection, as it establishes the theoretical foundation of the study and evaluates its novelty and relevance within the broader academic context. Scientific research typically involves successive methodological phases, among which the literature review plays a fundamental role. It situates the study within its academic domain by systematically synthesizing prior work, identifying key contributions, limitations, and research trends, and ensuring methodological rigor (Barry et al., 2022; Blessing & Chakrabarti, 2009; Montaña et al., 2024).

The literature review in this study focuses on three core thematic areas:

- 1) Design practices and research gaps in green building and affordable housing in Cambodia;
- 2) Application of LCA frameworks in the building industry and strategies for reducing environmental impacts;
- 3) Simplification approaches for LCA in buildings and associated recommendations.

A state-of-the-art review of green building and affordable housing design was conducted to understand current practices within the Cambodian construction sector. This review examines how green building principles are implemented and the extent to which they are integrated into existing design and construction processes. Similarly, the review of affordable housing investigates its current status, development trends, and implementation challenges. Together, these analyses provide a comprehensive understanding of existing practices, barriers, and opportunities for improvement. This state-of-the-art assessment highlights current design practices, identifies challenges and barriers, and reveals opportunities where the outcomes of this research may be applied. Furthermore, it enables the identification of both practical gaps (in design and implementation) and scientific gaps (in academic research), particularly in a context where existing studies remain limited.

In relation to LCA, the literature review primarily focuses on understanding its methodological framework and its application within the building sector. A thorough investigation of LCA is essential to this study, as it forms a central component of the research methodology. Various sources were consulted, including international standards, technical reports, guidelines, case studies, databases, and software tools. Key standards and frameworks considered include ISO 14040 and ISO 14044 (ISO, 2006a, 2006b), EN 15804 and EN 15978 (CEN, 2012a, 2012b), and the Environmental Footprint (EF) method (CEN, 2019; Zampori & Pant, 2019). These references provide methodological guidance and support data acquisition for specific aspects of the study. In addition, existing case studies and feasibility studies were reviewed to understand practical applications of LCA in the building sector.

The identification of design strategies for reducing life cycle environmental impacts is further developed in Chapter 5, where LCA is applied to the first residential case study (a townhouse). Therefore, this aspect is not fully addressed in the initial literature review but is extended through empirical analysis.

Regarding LCA simplification, the review focuses on understanding recommended approaches, particularly those outlined in the EeBGuide. This includes examining different levels of LCA implementation and identifying appropriate simplification strategies for practical use in building design. Overall, the literature review enables the author to develop a comprehensive understanding of LCA frameworks, their application in the building sector, and the potential for simplified approaches. It also facilitates the identification of research gaps related to building LCA studies and the implementation of simplified LCA methodologies, particularly in developing country contexts.

### 3.3 SURVEY

The survey targeting construction professionals in Cambodia was conducted using a semi-structured interview format. These interviews were designed to collect contextual insights, professional perspectives, and detailed information, thereby enabling a deeper understanding of the research problems and objectives. This method was incorporated into the data collection process to avoid relying solely on conclusions drawn from the literature, which often suggests that green building design and affordable housing practices are either limited or insufficiently documented in the Cambodian context. Therefore, empirical validation through engagement with industry professionals was necessary to ensure scientific rigor. Professionals involved in building design and construction projects were interviewed to investigate their knowledge, familiarity, experience, and perceptions regarding green building and affordable housing. It was anticipated that different stakeholders would possess varying levels of knowledge and practical experience with these topics. Consequently, the interviews were designed to be flexible and adaptable to the diverse backgrounds of the participants.

A semi-structured interview approach was selected because it allows for both guided questioning and exploratory discussion. This flexibility enables the identification of issues that may not have been initially anticipated while also facilitating the collection of rich, in-depth insights related to the research questions. Semi-structured interviews are widely used in qualitative research due to their ability to capture participants' experiences and interpretations in a nuanced and context-specific manner (Mahat-Shamir et al., 2021; Mojtahed et al., 2014).

The interview questions were developed based on insights from the initial literature review and were refined through pilot interviews with academic experts who have partial experience in architectural design. A detailed description of the interview design including question structure, thematic sections, flow, procedures, and participant recruitment is provided in Chapter 4, as these elements are closely linked to the research findings. The full questionnaire is included in the Appendix A.

A total of forty interviews were conducted with construction professionals, categorized as architects, construction engineers, green building experts, and decision-makers. Due to the sensitivity of certain topics and the limited availability of participants, some professionals were initially hesitant to participate or to share information openly. To address this, informal one-to-one semi-structured interviews were adopted, ensuring anonymity and confidentiality. This approach facilitated a higher level of trust and engagement, ultimately contributing to a successful sample size. Out of fifty stakeholders initially contacted, forty agreed to participate, resulting in an 80% response rate. Detailed profiles of the interviewees are presented in Chapter 4.

The interviews were documented using questionnaire sheets and audio recordings. Audio recordings were used to ensure data completeness and to clarify responses during the data processing phase when necessary. The collected data were subsequently transcribed and analyzed using NVivo software, applying a thematic coding approach (QSR International Pty Ltd., 2014). Through this process, key themes and sub-themes were identified and interpreted as part of the study findings. In addition, specific quantitative and categorical data such as construction costs, sale prices, building types, levels of familiarity with key concepts, material recommendations, technologies, software usage, design approaches, and building typologies were analyzed using Microsoft Excel to support descriptive and comparative analysis.

A detailed overview of the survey framework and procedures is provided in Chapter 4 (Figure 4-2), where the results and their interpretation are presented.

### 3.4 LIFE CYCLE ASSESSMENT

Assessing the environmental impacts of construction projects requires a holistic approach, as these impacts are extensive and multidimensional. In this study, well-established and widely recognized methodological frameworks for the building sector were adopted. These include the ISO 14040–14044 standards (ISO, 2006b, 2006a), which define the principles and procedures for conducting LCA; EN 15978 (CEN, 2012b), which specifies system boundaries, life cycle stages, and modules for buildings; and the EF method version 3.0, aligned with the 2019 EN 15804+A2 revision, which defines impact categories and assessment methods (SimaPro, 2026; Zampori & Pant, 2019). These standards and methods were selected due to their robustness, comprehensive scope, and widespread application in building LCA studies worldwide. International efforts to harmonize building LCA practices are largely based on frameworks such as the ISO 14000 series and EN 15978 (Röck et al., 2020). In contrast, there is currently no unified set of guidelines for LCA application in the building sector within Asia, where previous studies have employed and adopted diverse approaches.

Chapters 5 and 6 present detailed applications of the LCA framework for the two case studies; a townhouse and an apartment building, respectively. This section focuses on the general LCA methodology, including data collection, analytical procedures, assumptions, tools, and databases used for both case studies.

A process-based LCA approach was adopted in this study, as it is the most commonly used method in LCA research, including within the building sector (Abd Rashid & Yusoff, 2015; Abd Rashid, 2017; Suh & Nakamura, 2007). The study utilized several software tools: Microsoft Excel for data processing, AutoCAD and SketchUp for 2D and 3D modeling, and SimaPro (PhD license, version 9.4.0.2) for LCA modeling and analysis. SimaPro was selected due to its flexibility, ability to model systems at different levels of detail, and access to comprehensive databases such as ecoinvent (ecoinvent, 2026; SimaPro, 2026). As one of the most established LCA software tools, SimaPro allows adaptation to different regional contexts through appropriate dataset selection (Abd Rashid, 2017). The software is linked to several databases, including Agri-footprint 5, ecoinvent 3, EU and DK input-output databases, and the USLCI database. In this study, the ecoinvent database version 3.8 (allocation, cut-off by classification – system and unit) was used. The selection and relevance of these tools and databases have been discussed in the literature review chapter.

### 3.4.1 Scenario definition for impact reduction strategies

The definition of alternative scenarios aimed at reducing life cycle environmental impacts constitutes a key component of this LCA study. In addition to evaluating the baseline environmental performance of the case-study buildings, the study incorporates scenario-based LCA modeling to identify potential improvements aligned with green building objectives. The scenarios were developed based on feasibility considerations derived from on-site investigations, ensuring their applicability within the local context. They were also informed by findings from the literature review, particularly regarding building design strategies that influence environmental performance. Furthermore, this approach addresses a research gap by incorporating a comprehensive set of scenarios evaluated across multiple life cycle stages and environmental indicators.

While the scenarios are adapted differently for each case study, they are based on a consistent conceptual framework. As described in Chapters 5, 6, and 7, six scenarios were defined:

- Reference scenario
- Strategy 1: Material optimization and reduction of finishing materials
- Strategy 2: Use of environmentally friendly and bio-based materials
- Strategy 3: Adoption of lightweight timber structures
- Strategy 4: Integration of renewable energy systems
- Strategy 5: Combined strategies

### 3.4.2 Comparative LCA study

A comparative LCA analysis was conducted after obtaining the Life Cycle Impact Assessment (LCIA) results for both case studies. This analysis examines three levels of LCA detail: screening, simplified, and complete LCA. Comparisons were performed using characterized results expressed as contributions across life cycle stages. Five environmental indicators: climate change,

particulate matter, acidification, water use, and resource use – fossils were analyzed, along with an aggregated single-score indicator representing total environmental impact. The same LCA framework (ISO 14040-14044 and EN 15978-15840) was applied across all levels to ensure methodological consistency. However, the comparative analysis follows the EeBGuide guidance document (Wittstock et al., 2012), which provides guidance on system boundaries, life cycle stages, and building components for different levels of LCA detail. This approach allows for the evaluation of variations in results across the three LCA levels and supports the assessment of simplified LCA approaches. Further methodological details specific to the comparative analysis are provided in Chapter 7.

### 3.4.3 Goal and scope definition

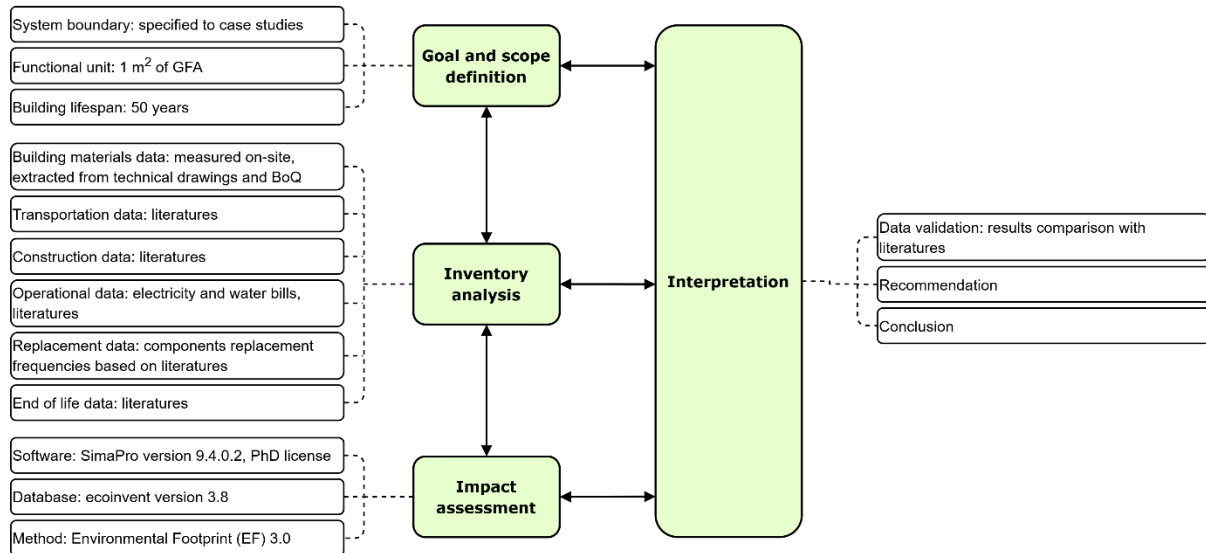
With reference to the Introduction chapter, the overall goal of this LCA study is to evaluate and establish benchmark values for sixteen environmental impact categories associated with conventional residential buildings in Cambodia, within defined system boundaries. In addition, the study aims to identify design strategies that reduce life cycle environmental impacts and contribute to the advancement of green building practices. A further objective is to evaluate simplified LCA approaches, namely screening and simplified LCA, to enable early-stage estimation of building environmental impacts. These approaches are intended to support decision-making during the design phase by providing accessible and practical assessment tools.

The research design, combining a case study methodology with the LCA framework, was developed to achieve these objectives, as illustrated in Figure 3-1. Figure 3-2 summarizes the data requirements corresponding to the four fundamental phases of the LCA framework. The system boundaries differ between the two case studies. For the townhouse, the LCA includes the production, construction, and use stages, with specific life cycle modules considered. For the apartment building, the assessment follows a cradle-to-grave approach, also with defined module inclusions. The EN 15978 standard was used to guide the classification of life cycle stages and modules in both cases (CEN, 2012b). Detailed justifications for the inclusion and exclusion of specific modules are provided in the respective case study chapters.

Defining an appropriate functional unit can be challenging due to variations in materials and construction technologies across buildings. In this study, the functional unit is defined as 1 m<sup>2</sup> of gross floor area (GFA), consistent with previous building LCA studies (Abd Rashid et al., 2017; Tulevech et al., 2018; Viriyaraj et al., 2024; Wan Omar, 2018). This unit enables comparison of results and supports future benchmarking. The GFA is defined as the total floor area enclosed within the building envelope, including external walls but excluding the roof area.

The building lifespan varies across studies and may depend on construction quality and housing standards. While reported lifespans range from approximately 20 to 100 years, a reference study period of 50 years is most commonly adopted in LCA studies of residential and commercial buildings, particularly in Southeast Asia (Abd Rashid et al., 2017; Tevis et al., 2019; Viriyaraj et al., 2024). A systematic review by Satola et al. (2021) found that nearly 60% of residential case

studies in tropical and subtropical climates use a 50-year lifespan (Satola et al., 2021). Accordingly, a 50-year reference study period is adopted in this study. The application of linear harmonization of embodied GHG emissions to this reference period enhances the comparability of results across case studies.



**Figure 3-2.** LCA framework.

### 3.4.4 Life cycle inventory

The two case-study buildings are located in Phnom Penh, the capital city of Cambodia, within a hot and humid tropical climate. Although constructed nearly twenty years apart, both buildings employ similar construction methods and conventional materials (e.g., cement, aggregates, sand, bricks, tiles, steel, and glass). Therefore, it is assumed that their construction techniques and material types are sufficiently comparable for the purposes of this study.

LCA guidelines do not prescribe a single standardized method for collecting building material data for Life Cycle Inventory (LCI) modeling. Consequently, this study adopts multiple data collection approaches tailored to the availability and quality of data for each case study. For the townhouse, where technical drawings and bills of quantities (BoQ) were not available, data collection began with on-site measurements. The collected measurements were systematically recorded and organized in Microsoft Excel, and subsequently used to develop 2D and 3D models of the building. These models enabled the estimation of material quantities required to construct a comprehensive BoQ. Since manual quantity take-offs are time-consuming and prone to errors, a model-based approach was adopted to improve accuracy and efficiency. For the apartment building, partial documentation including BoQ and 2D/3D drawings, was available. In this case, the primary task involved extracting and consolidating data to establish a detailed bill of materials (BoM) for each building component. However, this process was complicated by the presence of multiple document versions and incomplete or inconsistent information, making it challenging and time-intensive to identify accurate material specifications and quantities.

The finalized LCI datasets, compiled in Excel, were then used as input for modeling in SimaPro. Detailed descriptions of building components, material types, and quantities for both case studies are provided in their respective chapters.

### **1) Production and construction stage**

Life cycle modules A1 (raw material acquisition) and A3 (manufacturing) were jointly reported as the material production and modeled using the ecoinvent database. Transportation data for life cycle modules A2 (raw material transport), A4 (transport to construction site), and C2 (transport to disposal) were based on literature sources and justified assumptions. Estimation methods included consultation with project stakeholders, selection of nearest suppliers, use of national averages, and reference to previous studies (Abd Rashid, 2017). Construction process data for module A5 (construction and installation) were also derived from literature. A 5% material waste factor was assumed to account for losses due to handling, cutting, errors, and inefficiencies during construction, consistent with previous studies (Rossi et al., 2012; Yardimci & Kurucay, 2024). This waste factor was incorporated into the LCI calculations based on extracted BoQ data.

### **2) Use stage**

Operational data for electricity and water consumption were assumed to remain constant over the building lifespan. This simplification is widely adopted in LCA studies due to data limitations and modeling constraints (Asdrubali & Grazieschi, 2020; Omrany et al., 2020). Consumption data were derived from utility bills where available. For the apartment building, detailed energy consumption related to specific building services (e.g., HVAC, lighting, elevators, appliances, and cooking) was not available and therefore not disaggregated. Instead, total electricity consumption was used as a proxy for operational energy use.

Replacement activities (module B4) were included for major building components, such as roofing, windows, and surface finishes (e.g., painting), based on literature recommendations. Minor components and activities such as appliance replacement, cleaning processes, and wastewater treatment were excluded due to data limitations and their relatively lower contribution to total impacts. This approach is consistent with common practices in building LCA studies, where emphasis is placed on dominant contributors such as operational energy (B6). Due to limited availability of local data on material service life, replacement cycles were based on literature values and standard databases (Blengini & Di Carlo, 2010; Hoxha et al., 2017).

### **3) End of life stage**

The end of life stage (modules C1-C4) was modeled based on literature assumptions. In the Cambodian context, demolition and recycling practices for residential buildings are limited. Therefore, demolition (C1) and transport (C2) data were derived from literature, while 100% of demolition waste was assumed to be disposed of in landfill, with no recycling or recovery processes (i.e., module C3 excluded). Disposal processes (C4) were modeled using the ecoinvent database. Detailed assumptions for end of life modeling are provided in Chapter 6. Overall, the LCI

phase encompassing data collection, model development, quantity estimation (BoQ/BoM), and LCA modeling, was the most time-consuming and complex component of this research. This highlights the need for improved tools, data availability, and streamlined methodologies to support LCA implementation in building design.

### 3.4.5 Life cycle impact assessment

The selection of environmental indicators in building LCA is partly subjective but remains aligned with ISO recommendations for Life Cycle Impact Assessment (LCIA) methodologies. LCIA is commonly conducted using two main approaches: problem-oriented (midpoint) and damage-oriented (endpoint). Midpoint indicators represent environmental impacts at an intermediate point in the cause-effect chain, following the LCI and preceding endpoint impacts (Abd Rashid, 2017; Bare et al., 2000). In this study, LCIA is conducted exclusively at the midpoint level.

Previous studies have applied varying sets of impact categories; however, commonly included indicators typically comprise global warming potential, acidification, eutrophication, and ozone depletion. The EN 15804 standard aligns its LCIA framework with the EF method, which includes ten core and six additional environmental impact categories (CEN, 2019; Mirzaie, 2022; Zampori & Pant, 2019). In this study, the EF method version 3.0 was used to assess the environmental impacts of both case studies. Results are evaluated at three levels: characterized, normalized, and weighted values. The EF 3.0 method was selected because it provides a comprehensive set of sixteen environmental impact categories, enabling a more complete assessment of the environmental performance of conventional residential buildings in Cambodia, compared to studies that rely on a limited number of indicators.

The characterization factors, normalization values, and weighting sets used in this study are those embedded in the SimaPro software (Sala et al., 2018; Sala et al., 2017; SimaPro, 2026). These are directly applied in the LCIA calculations presented in Chapters 5 and 6. In accordance with the Product Environmental Footprint Category Rules (PEFCR) Guidance version 6.3, long-term emissions (beyond 100 years) were excluded from the analysis (EC, 2017).

LCIA results were analyzed at multiple levels of detail. At the building level, results show the contribution of different life cycle stages and modules. At the life cycle stage level, the production stage is further disaggregated to assess the contribution of building components. At the component level, the contribution of individual construction materials is evaluated. This multi-level analysis is applied in detail in the second case study. Both characterized and normalized/weighted results were exported to spreadsheets to facilitate hotspot analysis. In this study, hotspots refer to the most significant environmental indicators, identified in accordance with the PEFCR Guidance version 6.3, based on their contribution to the total environmental impact expressed as a single-score result (in millipoints). Furthermore, results were analyzed both with and without toxicity-related impact categories, including freshwater ecotoxicity and human toxicity (cancer and non-cancer effects), as required by the EF method (EC, 2017). This approach allows for assessing the influence of toxicity indicators on overall results and improves

interpretability (Mirzaie, 2022). Finally, the most relevant life cycle stages, building components, and construction materials were identified based on their relative contributions across different impact categories.

### 3.4.6 Interpretation

The interpretation phase is the stage in which LCIA results are analyzed and compared, and conclusions and recommendations are derived in relation to the objectives and scope of the LCA study. This phase ensures that the results are meaningfully linked back to the research goals and decision-making context. In the first case study (Chapter 5), data validation is conducted by comparing the results with findings from previously published studies within similar regional and climatic contexts. This comparative approach supports the credibility and contextual relevance of the results. In addition, all assumptions and limitations associated with the LCI are explicitly documented in each case study.

All methodological choices, assumptions, and data sources are justified based on established LCA literature, relevant standards, and guidelines for building-related assessments, while also considering data availability constraints.

A critical review process is essential to ensure that the study complies with the ISO 14040–14044 standards. In this research, the work is subject to evaluation by both internal and external examiners. In addition, selected components of the methodology and results have been presented at scientific conferences. The LCA of the townhouse (Chapter 5) has also undergone multiple rounds of peer review through journal submission processes and has been progressively refined based on reviewer feedback. The final revised version of this work will be submitted for publication in relevant peer-reviewed journals. In addition, the research will be compiled as a doctoral thesis and made accessible through both online repositories and institutional libraries for academic reference.

## 3.5 CHAPTER CONCLUSION

This thesis adopts a mixed-methods approach, incorporating both qualitative and quantitative methods for data collection, analysis, and interpretation of results. The mixed-methods design is considered particularly appropriate for this study because it enables the integration of complementary perspectives from different research domains.

The qualitative component, based on surveys of construction professionals, focuses on understanding contextual aspects related to green building and affordable housing design, as well as their integration within the Cambodian construction sector. This approach is essential for capturing stakeholder perspectives, practices, and contextual challenges. The quantitative component, based on LCA, is used to evaluate the environmental impacts of buildings and to identify strategies for reducing life cycle impacts. This approach supports the development of evidence-based strategies for improving building environmental performance.

Furthermore, the LCA methodology is applied across three levels of analysis: screening, simplified, and complete LCA, to assess the effectiveness of LCA simplification approaches for early-stage design applications. This multi-level assessment supports the study's objective of demonstrating the potential of simplified LCAs tools for decision-making in building design. Overall, the combined use of qualitative and quantitative methods strengthens the robustness of the research findings and aligns with methodological approaches commonly applied in related studies within the field.

# 4

## Integration of green building design and affordable housing

This chapter examines the contextual relationship between green building design and affordable housing within the Cambodian construction sector. To develop a comprehensive understanding of these topics, a semi-structured interview approach was employed to gather insights from local construction professionals. Four groups of stakeholders; architects, construction engineers, green building experts, and decision-makers were included, with ten participants in each group. The collected data were systematically processed and analyzed to derive key findings. The results provide contextualized definitions and characteristics of green building design and affordable housing, as well as their integration within the Cambodian context. In addition, the study identifies relevant aspects such as design priorities, construction cost and housing price considerations, recommended materials and tools, and preferred residential typologies for green affordable housing.

Part of this chapter was presented at the 13<sup>th</sup> International Conference on Sustainable Development and Planning, held in Seville, Spain, from 23-25 September 2024, and was subsequently published in *WIT Transactions on Ecology and the Environment*.

*Long, M., Han, V., Leclercq, P., & Reiter, S. (2024). Integration of Affordable Housing and Green Residential Building Design in the Construction Sector in Cambodia. In WIT Transactions on Ecology and the Environment. Volume 262 (pp. 215-227). <https://doi.org/10.2495/sdp240181>*

## 4.1 OVERVIEW OF CONSTRUCTION SECTOR IN CAMBODIA

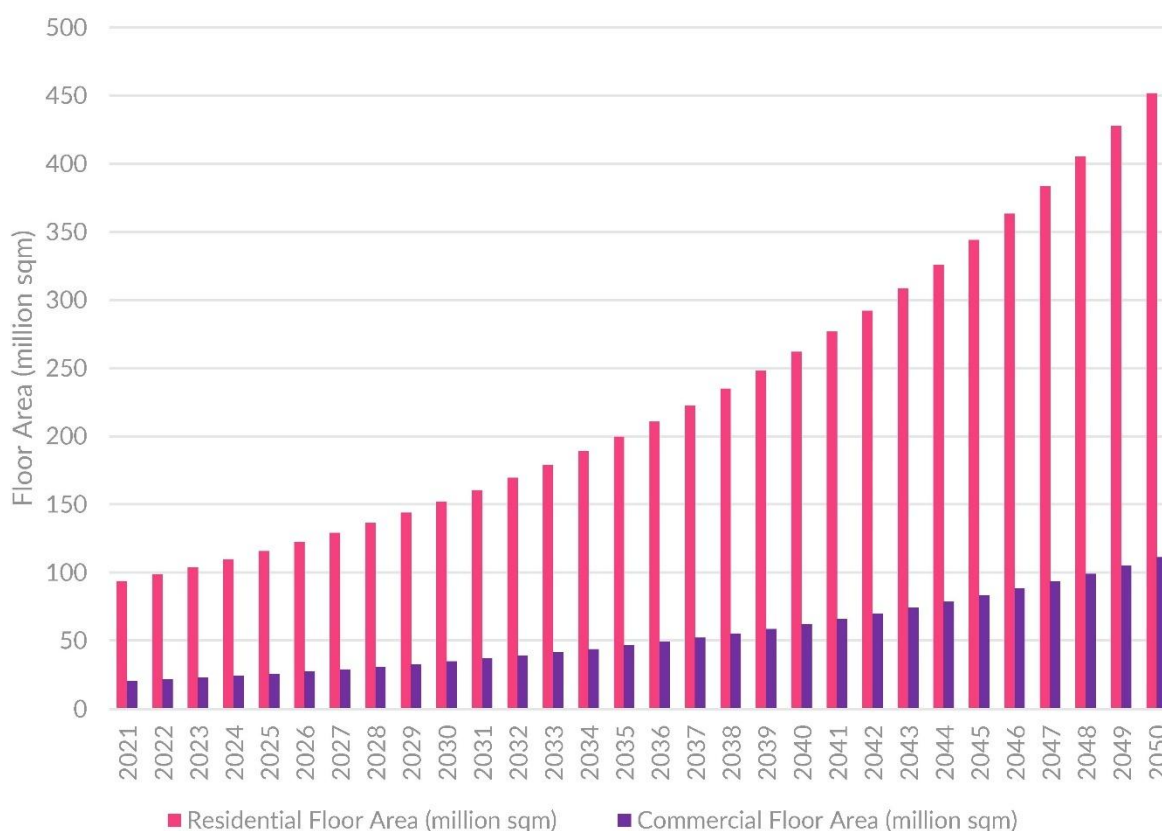
Urbanization in developing countries has experienced dramatic growth because of rapid population and world economic growth. The UN estimates that the global population will reach 8.5 billion by 2030, of which almost 60% of the population will be living in urban areas and will increase to 68% in 2050 (UN-Department of Economic and Social Affairs, 2024; World Bank, 2024). By that time, the UN Population Division projected that about 64% of developing countries and 86% of developed countries will be urbanized (Rahmadyani & Suhendri, 2020). The increasing speed and scale of urbanization will bring challenges related to the fulfillment of the basic needs of the cities such as accelerated demand for housing, viable infrastructure including transportation, energy systems, basic services including education and health care, and jobs (UN-Department of Economic and Social Affairs, 2024). People moving from rural to urban areas to have better socio-economic status through employment and education has made providing sufficient and affordable housing a major challenge of urbanization (Seng, 2020). The estimated 3 billion people will need new adequate housing and basic urban infrastructure by 2030, and Cambodia is not deviating from this challenge. Its capital city, Phnom Penh, is experiencing exponential growth and now has a population of 2.2 million, with numbers expected to continue rising.

In 2016, the World Bank Group upgraded Cambodia's status from a "low-income country" to a "lower-middle-income country" due to its significant poverty reduction and robust economic growth (Waibel, 2017). This reclassification coincided with a construction boom, particularly in the capital city. Building expansion is crucial as the Global Green Growth Institute and others predicted that the country's urban population will double by 2030, raising concerns about housing shortages and under-supply infrastructure. Cambodia adopted a national policy to promote the development of housing projects and the government forecasted that the capital city will demand some 800,000 new units to meet housing needs by 2030 (The Phnom Penh Post, 2024).

The groups of population that urgently need affordable homes, low- to middle-income people, and vulnerable groups, access fewer quality housing and well-being living opportunities (Kol & Brugman, 2022). In Phnom Penh, the financialization of the housing market through international investments has shifted housing construction to cater to foreign and elite groups instead of the local population. This makes housing access particularly difficult for the urban poor due to their low and unstable incomes and unenforceable land rights. Currently, most housing units are unaffordable for 60 to 70% of the population, presenting a significant challenge (GGGI et al., 2022). Besides the unaffordability challenge, the questions concerning the cost of construction, occupant health and comfort, and design standards of the building remain.

Even though the building sector is significant for economic growth, it should follow the principle of sustainable development and it is crucial to make the city inclusive to everyone (Abd Rashid et al., 2013). The global green movement has prioritized green building due to its ability to meet building demands while mitigating the negative environmental impacts of the construction

industry (Nguyen & Gray, 2016). To address its development challenges, Cambodia must adopt green building practices as part of its strategy to achieve sustainable development. However, there are few activities and limited knowledge and awareness of sustainable buildings in the construction sector of Cambodia (Durdyev et al., 2018; Waibel, 2017). The construction boom in the capital city lacks attention to sustainability and will have consequences in the near future. The construction laws and regulations include only quality, security, and safety of the building construction but it does not consider the performance of the building (for example: energy efficiency, human comfort, and low carbon emission), sustainability aspect, as well as green building criteria (NCSD/Ministry of Environment of Cambodia, 2021).



**Figure 4-1.** Forecast of increasing building floor areas by 2050 in Cambodia (GGGI et al., 2025).

Based on Cambodia Real Estate shared in 2021, more than 50% out of 258 projects under construction were in the residential segment and there are two affordable housing projects in the city and three in the province (Cambodia Investment Review, 2022; The Phom Penh Post, 2021). Between 2021 and 2050, the total building floor area is anticipated to increase by nearly 400%, rising from 115 million square meters in 2021 to 563 million square meters in 2050 (Figure 4-1) (GGGI et al., 2025).

The challenge of providing comfortable and affordable (low-cost) housing in Phnom Penh remains significant, despite efforts under the Affordable Housing Policy (GGGI et al., 2022). A critical issue lies in making the development of affordable and green housing a priority and attractive to private investors. Existing shophouses, which are often classified as low-cost housing,

are typically not well designed in terms of energy efficiency and natural ventilation. Although a construction boom is currently underway, there is limited documented evidence that green building design is being systematically integrated into architectural design and property development plans. However, the ongoing updating of the Construction Code presents a valuable opportunity to incorporate green building concepts into regulation and the code.

In the construction sector of Cambodia, there is still the requirement of guidelines and regulations for constructing affordable housing in the perspective of environmentally sustainable building design and adequate housing elements, and a recognized standard of affordable housing practice and policy. Meanwhile, the relevant sectors responsible for the affordable housing project development are facing a vague definition of affordable housing, unfixed sale price, not defined building typology, lack of standards and construction techniques, and missing the urban quality of life for people. This encourages engagement and investment from relevant stakeholders, both public authorities and the private sector, to support the development of the housing sector.

## 4.2 SURVEY ON GREEN BUILDING DESIGN AND AFFORDABLE HOUSING SECTOR

The objectives of this chapter are to define the characteristics of and provide clear definitions for affordable housing and green buildings, as well as to identify the main focus areas of green affordable housing. In addition, the chapter examines the construction costs and sale prices of the studied building types, green affordable housing typologies, and recommended materials, technologies, and design software, as suggested by construction professionals. Furthermore, the chapter explores stakeholders' awareness of these topics, including their self-reported levels of knowledge.

This study aims to address a research gap in the studies on affordable housing in Cambodia including unavailable access to data on the state of the housing sale market, no existing official categorization of housing unit types, missing key stakeholders for interview research (Traub & Sweeting, 2020), and the lack of personal accounts from Cambodian critically analyzing their situations (Boverman & Lazenby, 2020). Moreover, the sustainable building construction and green building implementation are still very limited and in the process of ongoing discussions in developing countries such as Cambodia (NCSD/Ministry of Environment of Cambodia, 2021; Waibel, 2017). Based on the mentioned problem and lack, this study will focus on a deeper understanding of concepts of affordable housing and green building, as well as the implementation of green affordable housing design in the construction sector of Cambodia. Therefore, several research questions arise:

- To what extent are construction professionals in Cambodia aware of affordable housing concepts, green building design principles, and their integration into construction practice?
- How are affordable housing and green buildings in the Cambodian context characterized and defined?

- Which design, construction techniques, materials, and strategy should be focused on for green affordable housing projects in Cambodia?
- What is the recognized construction cost and sale price of affordable housing, green building, and green affordable housing by Cambodian construction professionals?
- Which residential typology of green affordable housing can be identified?

#### 4.2.1 Survey protocol and semi-structured interview

The global survey adopts a qualitative approach aimed at gathering participants' points of view and understanding of green building design and the affordable housing sector through semi-structured interviews. The interviews followed an exploratory approach and were conducted based on an interview guide and predefined hypotheses. The survey targeted construction professionals, including architects, engineers, green building experts and practitioners, as well as decision-makers.

The survey analyzes several aspects, including participants' involvement in building projects throughout their professional experience; their familiarity with and knowledge of the study topics; their interpretations, characteristics, and definitions of affordable housing and green building design; construction costs and sale prices of different building types; the main focus areas of green affordable housing design; the identification of green affordable housing typologies; recommended materials and technologies; the ranking of materials based on suitability for green affordable housing; and examples of green buildings and affordable housing projects in Cambodia.

The semi-structured interviews were conducted between January and March 2024. Participants were contacted through social media platforms such as Messenger, LinkedIn, and Telegram, as well as through existing professional networks.

The semi-structured interview consisted of six main sections: (1) introduction, (2) affordable housing, (3) green building design, (4) compatibility between affordable housing and green building design, (5) examples of affordable housing and green residential buildings in Cambodia, and (6) comments, feedback, interests, and suggestions. In total, 23 questions were included in the interview. The complete interview guide is provided in Appendix A. The questions in each section are described as follows.

##### Section 1: Introduction

This section included questions related to general information, such as the interviewee's name, professional title, current role and position within their organization, years of experience in the construction sector, and the types of building and construction projects they most frequently work on or design.

## Section 2: Affordable Housing

This section addressed the following topics:

- Familiarity with and prior knowledge of affordable housing
- Experience working on or practicing affordable housing projects
- Self-assessed level of knowledge regarding affordable housing
- Characteristics and keywords associated with affordable housing from the participant's perspective
- Typical construction cost per square meter (m<sup>2</sup>)
- Construction cost per square meter (m<sup>2</sup>) and sale price per square meter (m<sup>2</sup>) of affordable housing

## Section 3: Green Building Design

This section included the following questions:

- Familiarity with and prior knowledge of green building design
- Self-assessed level of knowledge regarding green building design
- Characteristics and keywords associated with green building design from the participant's perspective
- Construction cost per square meter (m<sup>2</sup>) and sale price per square meter (m<sup>2</sup>) of green buildings

## Section 4: Compatibility between Affordable Housing and Green Building Design

This section explored whether affordable housing and green building design are compatible. If participants responded affirmatively, follow-up questions addressed:

- Key focus areas and strategies for integrating green building design into affordable housing
- Types of materials and technologies suitable for green affordable housing
- Ranking of ten pre-selected materials from most to least suitable for green affordable housing design
- Residential typologies of green affordable housing
- Construction cost per square meter (m<sup>2</sup>) and sale price per square meter (m<sup>2</sup>) of green affordable housing

## Section 5: Examples of Affordable Housing and Green Residential Buildings

Participants were invited to provide examples of affordable housing and green residential building projects in Cambodia. Information could include the project name, photographs, or references to publicly accessible sources.

## Section 6: Comments, Feedback, Interests, and Suggestions

This final section was open-ended, allowing participants to share additional insights, feedback, interests, or recommendations related to the study topics.

A total of 40 participants were interviewed over approximately 24 hours of interview sessions. The participants were categorized into four groups: (1) architects (Arch), (2) civil and construction engineers (Eng), (3) green building experts and practitioners (GB), and (4) decision-makers (DM). Details of the participants' profiles including their assigned acronym and identification number, position within their organization or institution, and years of professional experience are presented in Table 4-1.

Participant selection criteria were defined as follows: architects were required to have experience in residential building design; civil and construction engineers were required to be actively involved in building construction; green building experts and practitioners were required to work in green building design or green building certification; and decision-makers were required to be involved in the construction sector, particularly in policy-making, permitting, or green building certification.

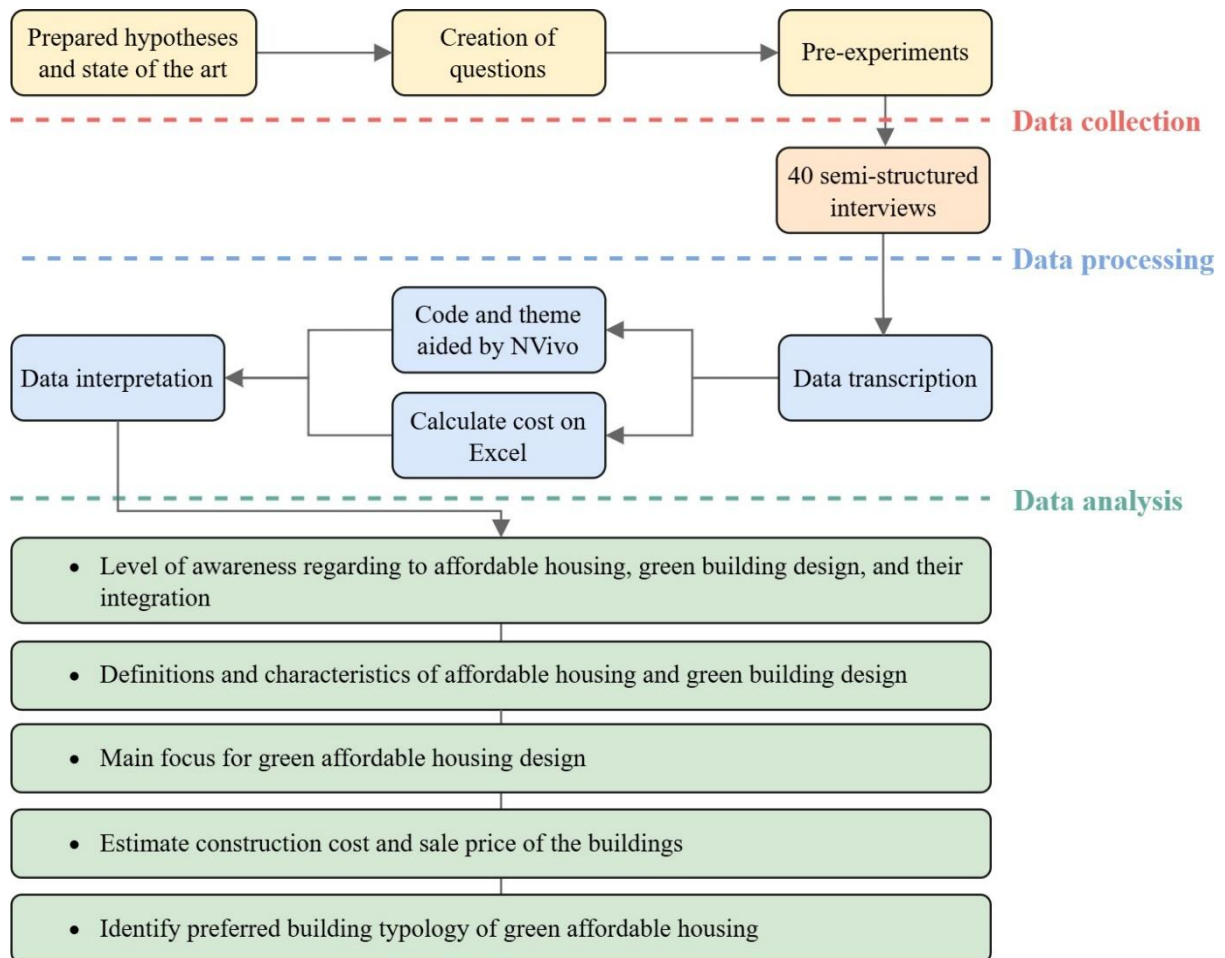
Most architects who participated in the survey were employed in private companies. Their professional experience varied, with an average of 5.6 years. While a few participants were recently graduated, the majority had between 2.5 and 7 years of experience, with the exception of one participant (Arch3), who reported 25 years of experience. The engineering group exhibited diverse roles and responsibilities. Their professional experience ranged from 3 to 11 years, with an average of approximately 6 years. Overall, the variation in years of experience within this group was relatively limited. Among the green building expert group, the average professional experience was 7 years. Two participants reported notably longer experience, with 11 and 20 years in the field, respectively. Most participants in this group occupied senior or managerial positions within their organizations. The decision-maker group consisted primarily of individuals in top management positions, with an average of 18 years of professional experience. Two participants in this group reported more than 30 years of experience in the field. Overall, 10 out of the 40 participants had more than 10 years of professional experience. Female representation was limited, with only five female participants included in the study.

**Table 4-1.** *Participant profiles.*

No	ID	Gender	Designation	Years of experiences
1	Arch1	Male	Technical Architect	2.5
2	Arch2	Male	Senior architect	7
3	Arch3	Male	Architect and urbanist	25
4	Arch4	Male	Architectural designer	3.5
5	Arch5	Male	Junior architect	0.5
6	Arch6	Male	Site architect	0.5
7	Arch7	Female	Senior architect	4.5
8	Arch8	Female	Senior architect	6
9	Arch9	Male	Architectural designer	4

10	Arch10	Male	Architect	2.5
11	Eng1	Male	Site engineer	7
12	Eng2	Female	Quantity surveyor	4.5
13	Eng3	Male	Site supervisor	4
14	Eng4	Male	Senior structural engineer	5
15	Eng5	Male	Site engineer	3
16	Eng6	Male	Site engineer	7
17	Eng7	Male	Technical manager	11
18	Eng8	Male	Engineering advisory	5
19	Eng9	Male	Structural and site engineer	5
20	Eng10	Male	Technical designer and project manager	5
21	GB1	Male	Design manager	11
22	GB2	Male	Founder of architecture firm	5
23	GB3	Male	Senior Architect	7
24	GB4	Male	Junior architect	2
25	GB5	Male	Co-founder of architecture firm	4
26	GB6	Male	Senior project engineer	3
27	GB7	Male	Chairman and CEO	20
28	GB8	Male	Senior Architect	6
29	GB9	Male	Director	9
30	GB10	Female	Team leader	3
31	DM1	Male	Architect and urbanist	23
32	DM2	Male	Founding director	36
33	DM3	Male	Ministry officer	7
34	DM4	Male	Chairman	27
35	DM5	Male	Deputy director	4
36	DM6	Male	Founder and CEO	27
37	DM7	Male	Urban environmentalist	3
38	DM8	Male	Urbanist	31
39	DM9	Male	General manager	8
40	DM10	Female	Design manager and managing director	15

Figure 4-2 outlines the execution of the research procedure. The interview questions were designed and pilot-tested through three preliminary interviews with a lecturer, a researcher, and a professor to ensure the collection of relevant data and to assess participants' understanding of the study questions. Based on the feedback obtained, the interview questions were subsequently refined and improved.



**Figure 4-2.** *The detailed research procedure of the study.*

Data collected from the semi-structured interviews were transcribed and summarized in an Excel file. For data interpretation, the transcripts were coded and categorized into specific themes using the NVivo platform, while the median values of construction costs were calculated in Excel. The results were analyzed in relation to the research questions. The transcription of data collected from the semi-structured interviews are available in Appendix A.

The development of the semi-structured interview questions was guided by the study objectives and an exploratory approach aimed at identifying the defining characteristics of affordable housing, green building design, and their integration. The following examples of interview question framework was designed and applied to identify key themes aligned with the study's research questions.

1. Self-reported level of awareness regarding to affordable housing and green building design
  - How much do you know about affordable housing in percentage (from 1 to 100%)?
  - How much do you know about green building design in percentage (from 1 to 100%)?
2. Affordable housing characteristic and definition

- Please give us characteristics and keywords of terms “Affordable housing” from your points of view.
3. Green building characteristic and definition
    - Please give us characteristics and keywords of terms “Green building design” from your points of view.
  4. Main focus for green affordable housing
    - Are the concepts of “Affordable housing” and “Green building design” compatible? If yes, what is your main focus and strategy to implement green building design to affordable housing?
  5. Construction cost and sale price
    - Can you tell us what is the usual construction cost per built area of 1 m<sup>2</sup> in Cambodia?
    - Can you tell us what is the construction cost and sale price of an affordable housing per built and usable area of 1 m<sup>2</sup> in Cambodia?
    - Can you tell us what is the construction cost and sale price of a green building per built and usable area of 1 m<sup>2</sup> in Cambodia?
    - Can you tell us what is the construction cost and sale price of a green affordable housing per built and usable area of 1 m<sup>2</sup> in Cambodia?
  6. Residential typology
    - What type of residential housing do you think should be used to create affordable green housing in Cambodia? (For example: terraced house, semi-detached house, detached house, apartment, high-rise building, etc.)

#### 4.2.2 Building projects

This section explains and summarizes the first set of survey results. It presents the types of building projects in which the survey participants are most frequently involved. To facilitate interpretation of the results, all projects are grouped according to their main functional building or project types, as presented in Table 4-2. The table categorizes projects by primary building or facility type, followed by the various specific projects within each category. In addition to building types, the table also includes projects related to renovation, urban planning, landscape design, interior design, infrastructure, and other related fields.

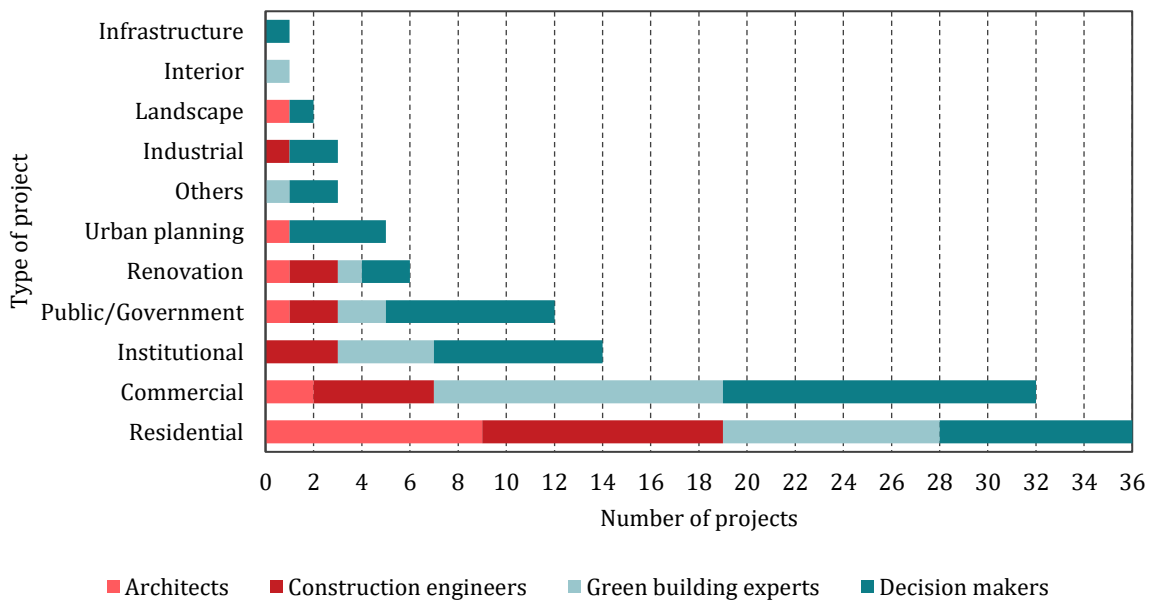
**Table 4-2.** *Categorize building projects by main type.*

<b>Type of buildings or other projects</b>	<b>Number of projects</b>
Residential: housing, apartments, green housing	36
Commercial: offices, retails, mixed-use	32
Institutional: school, hospital, university	14
Public/Government: public housing, civil building	12
Renovation	6
Urban planning	5
Others: unclassified or niche project	3
Industrial: factory, warehouse	3

Landscape	2
Interior	1
Infrastructure: roads, bridges, utilities	1

Figure 4-3 presents the types of buildings and related projects within the construction sector, as well as the number of projects in which the survey participants have been involved. According to the construction professionals, residential buildings constitute the most common project type, being the projects most frequently designed and constructed. Commercial buildings follow as another major project category frequently mentioned by participants. These findings indicate that residential and commercial buildings are the most commonly designed and built project types in the country, with approximately 80-90% of the surveyed construction professionals having worked on projects in these two categories.

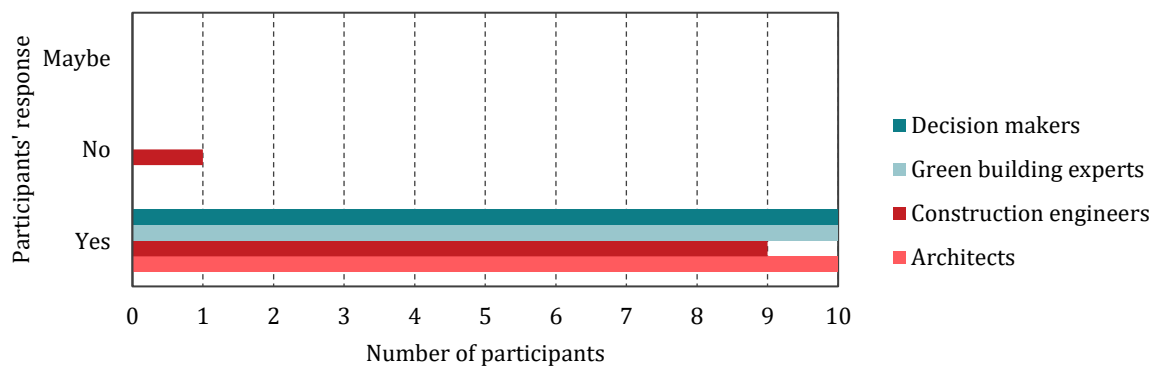
Institutional and public/government buildings represent the third most common group of projects, with approximately 30-35% of participants reporting experience in this category. Additionally, around 13-15% of participants have been involved in urban planning and building renovation projects, respectively. Although fewer in number compared to the major project categories, renovation and urban planning projects remain important areas of professional involvement. Notably, all participant groups reported some level of involvement in building renovation projects, whereas urban planning activities were limited to architects and decision-makers. It is also worth noting that decision-makers reported involvement in nearly all project types, with the exception of interior design work.



**Figure 4-3.** Type of building or facility projects in which construction professionals have been involved.

### 4.2.3 Affordable housing

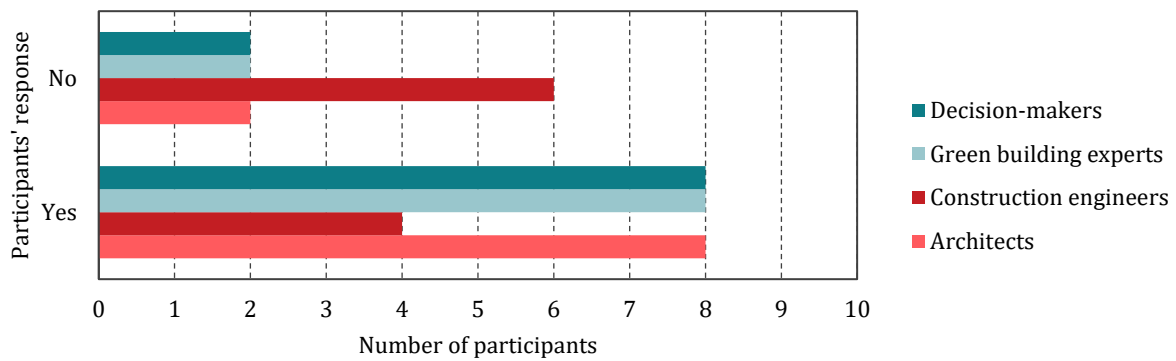
In the first part of the affordable housing section, we explore participants' familiarity with and prior exposure to the concept of affordable housing. Figure 4-4 shows the number of participants who reported that they had heard of affordable housing, had not heard of it, or were unsure. The results indicate that all participant groups were generally familiar with the topic, with the exception of one construction engineer who reported no prior knowledge. This suggests that, within the construction sector, the concept of affordable housing is not new and is generally recognized by professionals.



**Figure 4-4.** Familiar knowledge and hearing responses of affordable housing from participants.

In this section, we examine whether participants have experience with or involvement in affordable housing projects. Figure 4-5 shows that 8 out of 10 participants (80%) in the architect, green building expert, and decision-maker groups reported having experience working on affordable housing projects. This indicates that most professionals in these groups possess a background in affordable housing project design and may have contributed to policy-making or strategic planning for such projects. For green building experts, this experience may also include implementing green building design elements within their previous affordable housing projects.

In contrast, 6 out of 10 construction engineers reported no prior experience with affordable housing projects, leaving only 4 participants in this group who have worked on such projects. This suggests that involvement in affordable housing projects among construction engineers is relatively limited compared to the other professional groups.



**Figure 4-5.** Response of experience or not in affordable housing projects from participants.

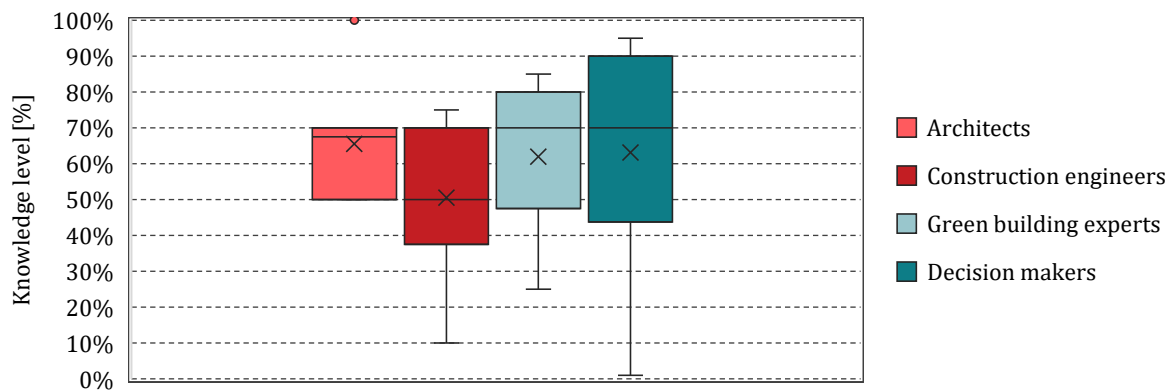
This section examines participants' self-assessed knowledge levels of affordable housing, measured on a scale from 1% (minimal knowledge or experience) to 100% (complete understanding or extensive experience). Figure 4-6 presents the distribution of knowledge levels reported by the four professional groups using median values. And, Table 4-3 presents the exact values of self-reported knowledge of affordable housing by professional groups.

**Table 4-3.** Self-reported knowledge of affordable housing by professional group.

Professional group	Median (%)	Mean (%)	Min-Max (%)
Architects	68	66	50-100
Construction engineers	50	51	10-75
Green building experts	70	62	25-85
Decision makers	70	63	1-95

The median knowledge level reported by architects was 68%, while both green building experts and decision makers reported higher median values of 70%, indicating a generally comparable and relatively high level of perceived familiarity with the topic across these three groups. In contrast, construction engineers reported a lower median knowledge level of approximately 50%, suggesting comparatively less self-assessed knowledge of affordable housing.

The architects' group exhibited a relatively narrow interquartile range, indicating more consistent self-assessment among participants, although one outlier reported a knowledge level of 100%. In comparison, construction engineers, green building experts, and decision makers showed wider distributions of responses, reflecting greater variability in perceived knowledge within these groups. Despite this variability, the central tendencies of green building experts and decision makers remained closely aligned.



**Figure 4-6.** Percentage distribution of participants' self-reported knowledge level regarding affordable housing.

A high percentage of participants reported familiarity with and prior experience in affordable housing, which contributed to more informed insights regarding the characteristics and definition of affordable housing.

Section 2 of the interviews focused on participants' perceptions of the characteristics, construction costs, and sale prices of affordable housing in Cambodia's construction sector. The objective was to investigate how participants define affordable housing, its construction cost, and the sale price per square meter (m<sup>2</sup>). For comparative purposes, the cost of normal construction, affordable housing, green buildings, and green affordable housing, as well as the sale price per m<sup>2</sup> of affordable housing are presented in Section 4.2.7.

The interview results were organized into main themes and sub-themes, as presented in Table 4-4. Sub-themes represent coded and grouped responses or key terms provided by the survey participants, while the main themes categorize these sub-themes to capture specific characteristics and avoid vague information. The frequency of mentions for each theme and sub-theme is reported in brackets.

From the interviews, 11 main themes and corresponding sub-themes were identified in defining and characterizing affordable housing. These are ranked as follows:

- 1) Architectural design and construction techniques
- 2) Affordable price
- 3) Enhancing quality of life
- 4) Location
- 5) Housing for low- to middle-income people
- 6) Comfort
- 7) Choice of materials
- 8) Housing for all
- 9) Energy consumption
- 10) Accessibility to public services and facilities
- 11) Safety and security

The main themes represent what affordable housing should achieve or embody, while the sub-themes highlight the specific considerations within each main theme.

Participants emphasized that architectural design is critical in affordable housing projects. Design considerations should prioritize efficient space layouts suitable for daily living, functional use within limited areas, and minimalistic yet practical design approaches. Integrating community engagement, local culture, and vernacular architectural elements were also recommended. Specific sustainable building techniques to employ in the projects were also highlighted as important.

In terms of construction, participants noted the importance of ensuring acceptable housing quality and durability. Regarding location, affordable housing should ideally be situated in urban or suburban areas, accessible yet safe, avoiding risky or hazardous locations. The use of affordable and locally available materials was considered significant, alongside minimizing energy consumption in housing operations. Illustrative responses from the interviews include:

*“Affordable housing has very limited living space and area because it is supposed to be a small house or apartment. That is why the design is important. Layout arrangement and functional design need to be efficient for users, effective, functional, accessible, and adequate.” (Participant Eng3)*

*“Even if your building design is good and attractive, if people are not comfortable living in it or it costs too much to maintain, it is not good. Considering minimal energy use in daily living is very important.” (Participant GB5)*

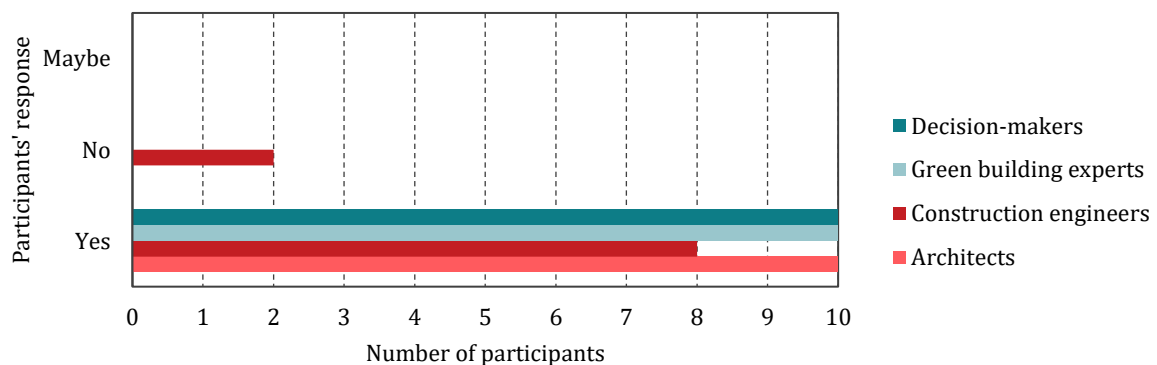
**Table 4-4.** Classified themes in the total list of characteristics and definition of affordable housing.

Themes	Sub-themes
1) Architectural design and construction (62)	• Effective space arrangement and functional (8)
	• Ensure the quality of housing (6)
	• Minimal design and style (5)
	• Integrate community sense (3)
	• Adapt to local culture and vernacular architecture (2)
	• Sustainable building design (2)
2) Affordable price (35)	
3) Enhance quality of life (24)	
4) Location (18)	• Locate in suburbs (5)
	• Not be at a risky location (1)
5) Housing for low to middle-income people (15)	
6) Be comfortable (14)	
7) Materials choice (12)	• Affordable materials (4)

	<ul style="list-style-type: none"> <li>Local materials (1)</li> </ul>
8) Housing for all (7)	
9) Energy consumption (5)	<ul style="list-style-type: none"> <li>Minimize energy consumption (2)</li> </ul>
10) Accessibility to public service and facility (4)	
11) Be secure (2)	

#### 4.2.4 Green building design

In the first part of the green building design section, we examine participants' familiarity with and prior exposure to the concept of green building design. Figure 4-7 shows the number of participants who reported that they had heard of green building design, had not heard of it, or were unsure. The results indicate that most participant groups are aware of and familiar with the topic, with the exception of two construction engineers who reported no prior knowledge. This suggests that while green building design is generally recognized among construction professionals, a small subset of civil and construction engineers remains unfamiliar with the concept.



**Figure 4-7.** Participants' familiarity with green building design.

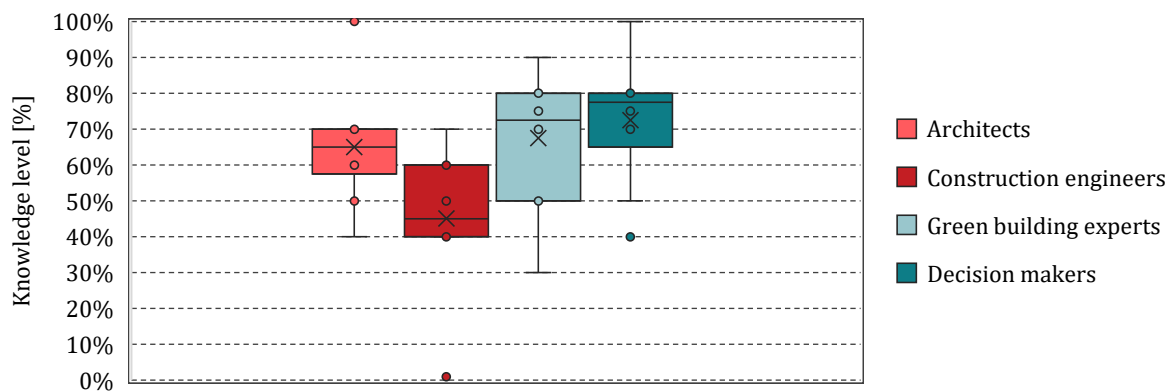
This section investigates participants' self-assessed knowledge levels of green building design, measured on a scale from 1% (minimum knowledge) to 100% (complete understanding or extensive experience). Figure 4-8 presents the distribution of knowledge levels reported by the four professional groups using median values. And, Table 4-5 presents the exact values of self-reported knowledge of green building design by professional groups.

**Table 4-5.** Self-reported knowledge of green building design by professional group.

Professional group	Median (%)	Mean (%)	Min-Max (%)
Architects	65	65	40-100
Construction engineers	45	45	1-70
Green building experts	73	68	30-90
Decision makers	78	73	40-100

The median knowledge level reported by architects was approximately 65%, while higher median values were observed for green building experts (73%) and decision makers (78%), indicating stronger perceived familiarity with green building design among these groups. In contrast, construction engineers reported a considerably lower median knowledge level of approximately 45%.

All professional groups exhibited wide ranges in their responses, reflecting substantial variability in individual self-assessments. A notably low outlier was observed among construction engineers, with one participant reporting a knowledge level of 1%, while high outliers reaching 100% were reported in other professional groups. Despite this variability, the median values indicate that architects and green building experts demonstrated broadly comparable levels of perceived knowledge, while decision makers reported the highest overall median knowledge level.



**Figure 4-8.** Percentage distribution of participants' self-reported knowledge level regarding green building design.

Section 3 of the interview focused on participants' perceptions of the characteristics and definition of green building design within the construction sector of Cambodia. The objective was to investigate how participants define green building design and which aspects they consider most important.

The interview results were analyzed and categorized into 11 main themes, with 25 sub-themes identified under certain themes. The themes, ranked from most to least mentioned, are as follows:

- 1) Architectural design and construction techniques
- 2) Resources savings
- 3) Materials consumption
- 4) Bioclimatic design
- 5) Greenery
- 6) Occupants
- 7) Minimizing environmental impact
- 8) Renewable energy
- 9) Sustainable development pillars
- 10) Waste management

## 11) Green building certification

Table 4-6 presents the themes and sub-themes along with their corresponding frequencies. Sub-themes provide detailed insights into what participants consider essential in green building design, highlighting areas of focus and related factors.

Architectural design and construction techniques (48 mentions) and saving (47 mentions) were the two most frequently cited aspects of green building design. Participants described architectural design in green buildings as emphasizing sustainable building design with environmental and eco-friendly approaches. Space planning should prioritize practicality and usability, while design choices should allow for feasible maintenance and incorporate minimalistic yet functional styles. Participants also highlighted the importance of site integration, adapting designs to local culture, society, and community needs, and applying sustainable construction techniques. High-rise buildings are commonly associated with green building projects in Cambodia, and participants noted that green building design principles are often applied to these types of buildings. Additionally, participants emphasized that flood protection measures should be incorporated in both the design and construction methods.

The theme of resources saving ranked second in frequency, encompassing energy, water, material, cost, land use, and maintenance savings. Participants stressed that such efficiencies are particularly important in Cambodia's construction sector. Materials consumption was identified as the third most cited theme, emphasizing the use of reusable and recyclable materials, eco-friendly and low-carbon materials, locally sourced materials, and natural products.

Other key considerations included occupants' comfort, well-being, social and community benefits, and safety. Additionally, participants highlighted the importance of bioclimatic design, integrating greenery, minimizing environmental impact, using renewable energy, adhering to sustainable development principles, managing waste, and achieving green building certification as essential parameters for green building projects. Illustrative participant responses include:

*"Green building design, of course, first uses sustainable building design and second sustainable construction techniques. These two parameters are very important, and designers and engineers must study them thoroughly." (Participant DM10)*

*"Savings can be achieved in green buildings in many ways: electricity, water, and maintenance in the daily life of occupants." (Participant Arch9)*

*"Green building is a building that uses any approach and design that is environmentally and eco-friendly. Moreover, there are many bioclimatic strategies that can be applied, such as natural ventilation, shading devices, natural light, and green spaces." (Participant GB7)*

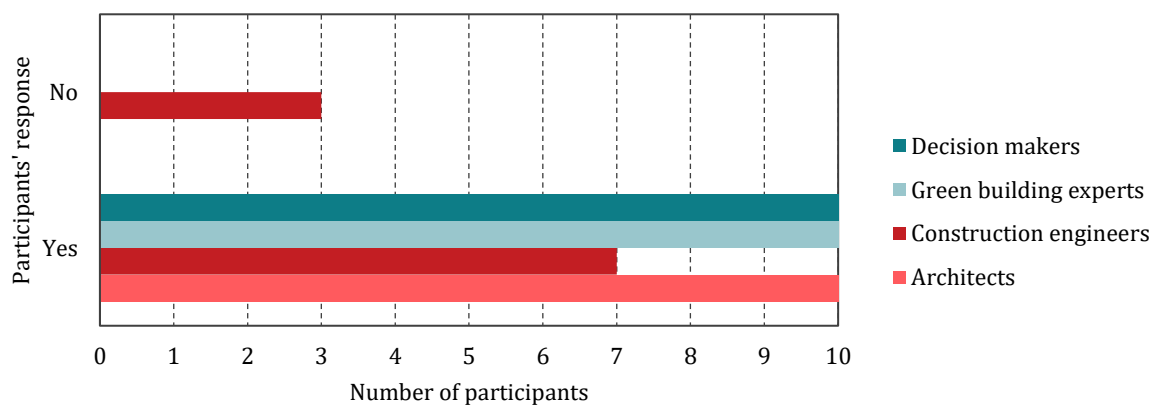
**Table 4-6.** *Classified themes in the total list of characteristics and definition of green building.*

<b>Themes</b>	<b>Sub-themes</b>
1) Architectural design and construction techniques (48)	• Sustainable building design (6)
	• Sustainable construction techniques (5)
	• Environmental and eco-friendly approach (4)
	• Practical and usable space design (2)
	• Site and surrounding integration (2)
	• Adapt to local culture, society, and people (1)
	• Feasible maintenance (1)
	• High-rise building (1)
	• Minimal design and style (1)
	• Protection against flood (1)
2) Resources savings (47)	• Saving energy (14)
	• Saving water (3)
	• Saving environment (2)
	• Saving materials consumption (2)
	• Saving cost (2)
	• Saving land use (1)
	• Saving maintenance (1)
3) Materials consumption (40)	• Reused and recycled materials (7)
	• Eco-friendly and low-carbon materials (6)
	• Local materials (2)
	• Natural products (2)
4) Bioclimatic design (25)	
5) Greenery (23)	
6) Occupants (20)	• Human comfort (3)
	• Social and community (2)
	• Well-being (2)
	• Security (1)
7) Minimize impact on the environment (17)	
8) Renewable energy (5)	
9) Sustainable development pillars (3)	
10) Waste management (3)	
11) Green building certification (2)	

## 4.2.5 Green affordable housing

In Section 4 of the interview, we investigated whether participants considered affordable housing and green building design to be compatible. Figure 4-9 presents participants' responses regarding the compatibility and integration of these two concepts. All participants in the architect, green building expert, and decision-maker groups (100%) agreed that affordable housing and green building design are fully compatible.

In contrast, 30% of participants in the construction engineer group believed that affordable housing and green building design are not compatible, indicating a "No" response. The remaining 70% of construction engineers, however, shared the same view as the other professional groups, affirming the compatibility of the two concepts.



**Figure 4-9.** Participants' perspective on compatibility of affordable housing and green building design.

Following the discussion on the compatibility of affordable housing and green building design, Section 4 of the interview explored participants' perspectives on green affordable housing in Cambodia's construction sector. The objective was to investigate priority criteria, potential implementation strategies, and integration of the two concepts. While this topic may present a challenge for participants, it was also an engaging exercise, requiring them to consider solutions that are both affordable and green.

The interview results were analyzed and categorized into 12 main themes and 27 sub-themes, ranked from most to least frequently mentioned:

- 1) Architectural design and construction techniques
- 2) Materials choice
- 3) Bioclimatic design
- 4) Quality of life
- 5) Resources saving
- 6) Greenery
- 7) Affordability
- 8) Minimizing environmental impact

- 9) Renewable energy
- 10) Rainwater harvesting
- 11) Waste management
- 12) Minimizing construction cost

Table 4-7 presents the detailed themes and sub-themes along with their frequencies. Each sub-theme provides specific insight into the meaning of the corresponding main theme.

Architectural design and construction techniques were the most frequently mentioned theme (71 mentions). Participants emphasized that green affordable housing should integrate community spaces, sustainable and eco-friendly design principles, and minimalistic but functional styles. Space optimization is particularly important, even within the constraints of affordability. Participants also noted that creative approaches are required to reconcile the dual objectives of affordability and green building design. Accessibility and compliance with quality standards were highlighted as key considerations in both architectural and construction practices.

Materials choice was the second most frequently cited theme (60 mentions). Participants stressed the importance of selecting local, affordable, reusable, recyclable, natural, eco-friendly, and, where possible, certified green materials.

Bioclimatic design (49 mentions) and quality of life (33 mentions) were also highly emphasized. Quality of life was associated with human comfort, social and community interactions, appropriate living spaces, environmental friendliness, accessibility, recreational opportunities, good indoor environment, and overall improvement of lifestyle. Resources savings including energy, materials, water, costs, and construction efficiency, was also highlighted as a key strategy for green affordable housing.

The remaining themes, greenery, affordability, minimizing environmental impact, renewable energy, rainwater harvesting, waste management, and minimizing construction cost, were considered additional critical strategies representing the main focus areas of green affordable housing. Illustrative participants' responses include:

*“Designing affordable housing to be a green building can be challenging during the design phase, especially when project developers are involved. However, many countries have already implemented such projects successfully. Green building does not have to be expensive. There are numerous local practices, techniques, and cultural approaches that make green buildings feasible and affordable.” (Participant DM4)*

*“Affordable housing primarily focuses on people’s income and economic considerations, not green building. If green building elements are added, people may not be able to afford it.” (Participant Eng1)*

**Table 4-7.** *Classified themes in the total list of characteristics and definition of green affordable housing.*

<b>Themes</b>	<b>Sub-themes</b>
1) Architectural design and construction techniques (71)	• Integrate community and common space (9)
	• Apply green, sustainable, and environmental design (8)
	• Minimal design and style (5)
	• Using design standards and construction techniques (4)
	• Maximize the space (3)
	• Adapt to affordable housing and green design (1)
	• Ensure quality of building (1)
	• Good accessibility in the building (1)
2) Materials choice (60)	• Local materials (7)
	• Reused, recycled, and recyclable materials (7)
	• Affordable materials (6)
	• Natural materials (6)
	• Eco-friendly materials (3)
	• Green labelled materials (1)
3) Bioclimatic design (49)	
4) Quality of life (33)	• Human comfort (4)
	• Social and community relationship (4)
	• Appropriate living space and shelter (3)
	• Environmental-friendly (2)
	• Accessible (1)
	• Entertainment (1)
	• Good ambiance and atmosphere (1)
	• Improve lifestyle (1)
5) Saving (33)	• Saving energy (9)
	• Saving materials (3)
	• Saving cost (2)
	• Saving water (2)
	• Saving construction techniques (1)
6) Greenery (20)	
7) Be affordable (8)	
8) Minimize impact to the environment (4)	
9) Renewable energy (4)	
10) Rain harvesting (3)	

11) Waste management (3)	
12) Minimize construction cost (1)	

After discussing the main focus and strategies for implementing green affordable housing, participants were asked about the materials that should be used in such projects in Cambodia. Figure 4-10 presents the types of materials mentioned and their frequencies across the four participant groups. The top five most recommended materials were wood, concrete, clay, bamboo, and earth. Following these, lightweight concrete, leaves, steel, and green concrete were also suggested, though with lower frequencies. The remaining materials were each mentioned only once. However, when these materials are regrouped according to their general nature and source; for example, wood with bamboo, concrete with lightweight concrete, and clay with earth, the combined frequency of wood and bamboo is the highest (18), followed by the other groups, each with a frequency of 13.

Among the top five materials, the architect group contributed most frequently, with a total of 15 mentions. Compared to construction engineers, green building experts, and decision-makers, architects demonstrated the greatest familiarity and precision regarding which materials should be employed in green affordable housing projects.

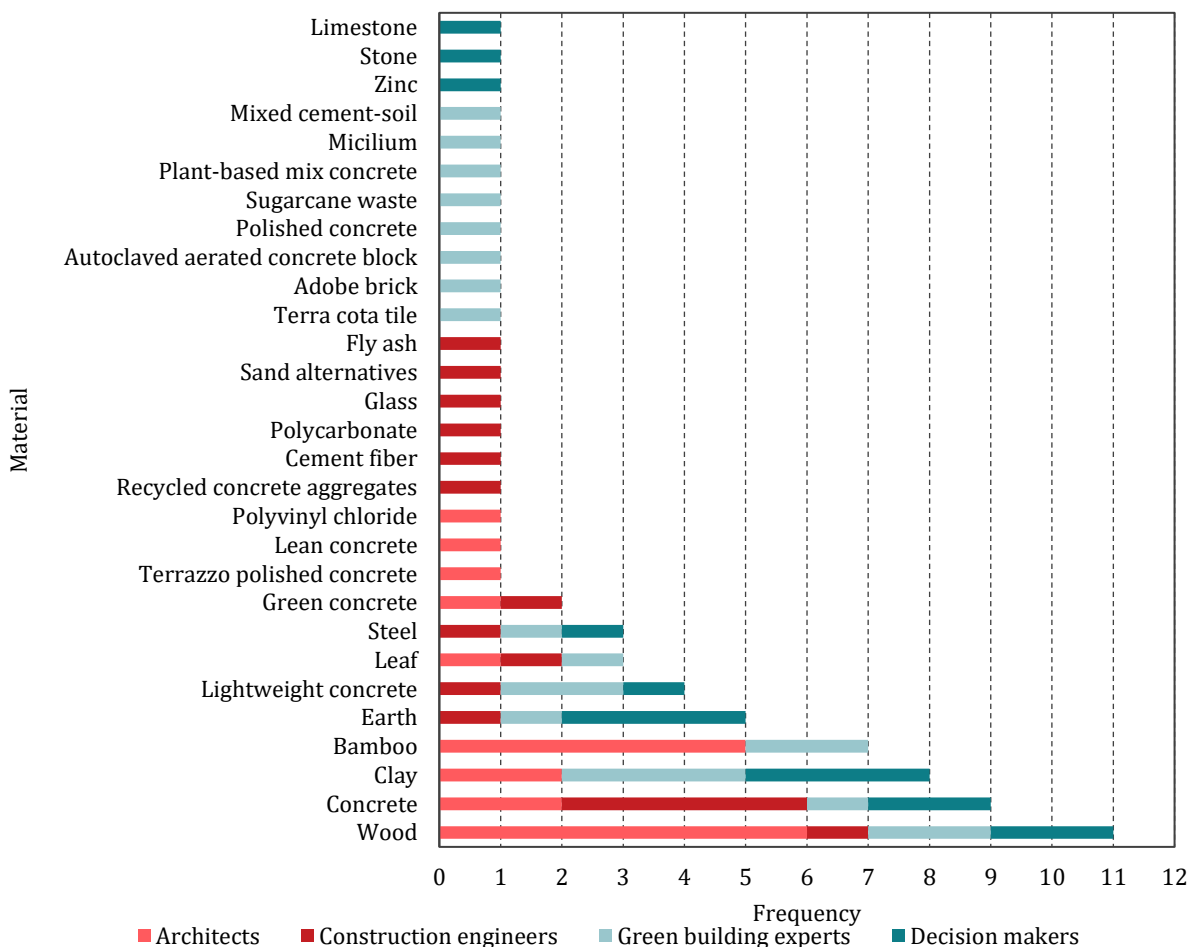
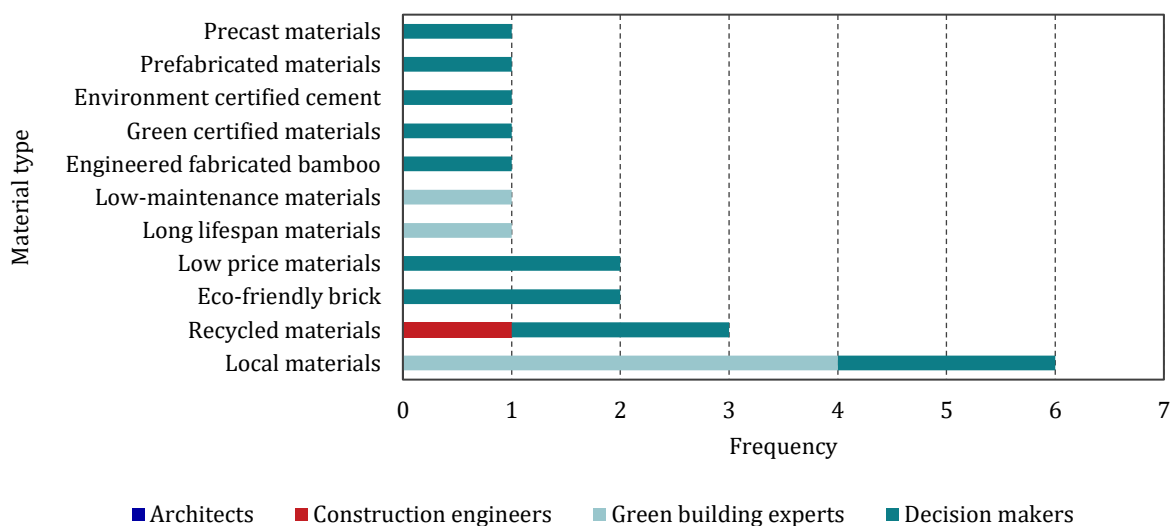


Figure 4-10. Recommended materials to be used in green affordable housing from participants.

In addition to specifying particular materials, participants also recommended several material types and alternatives. In these cases, participants mentioned only the general type of material rather than specifying particular materials within each type. These recommendations are presented in Figure 4-11. Local materials were the most frequently recommended, followed by recycled materials, eco-friendly bricks, and low-cost materials. While these materials are considered advantageous for green affordable housing, they were less frequently mentioned, which explains the lower frequencies recorded for each type.

Among the participant groups, green building experts and decision-makers provided the majority of these material-type recommendations. Notably, decision-makers contributed the widest variety of material types, as shown in Figure 4-11. In contrast, architects and construction engineers tended to provide more specific material recommendations rather than general categories.



**Figure 4-11.** Recommended material types to be used in green affordable housing from participants.

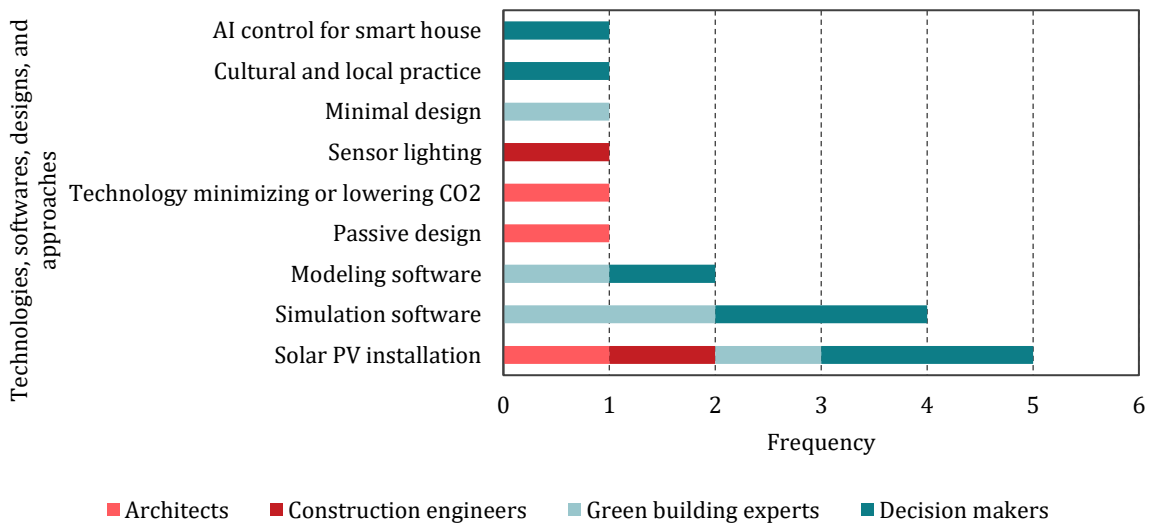
Participants also suggested several technologies, software, building designs, and approaches for green affordable housing design. Table 4-8 presents a detailed list of the recommended technologies, software for building simulation and modeling, passive design strategies, and minimal design specifications. Because participants provided a wide range of ideas, these suggestions were grouped into categories and their frequencies were recorded to facilitate analysis and interpretation of the results. The results indicate that solar PV panel installation was the most frequently recommended technology. Following this, building simulation software and modeling software were also highly recommended, making these the top three most frequently cited technologies and software tools. Other building designs and approaches were suggested by participants but were mentioned only once, indicating lower frequency of recommendation.

**Table 4-8.** Technologies, software, designs, and approaches suggested for green affordable housing design.

Technology, software, design, and approach	Details	Frequency
--	---------	-----------

Solar PV installation		5
Simulation software	EnergyPlus, EcoTech, design-stage energy consumption simulation, building performance simulation, BEE incorporation software	4
Modeling software	Rhino, Sketchup, AutoCAD, Revit	2
Passive design	Louvre and ventilation block, sun block, solar shading, façade and envelope, green roof,	1
Technology minimizing or lowering CO <sub>2</sub>		1
Sensor lighting		1
Minimal design	Wall without finishing materials	1
Cultural and local practice		1
AI control for smart house		1

Figure 4-12 presents the technologies, software-aided building simulation and modeling tools, building designs, and approaches recommended by survey participants for green affordable housing design. In terms of the distribution of responses across participant groups, decision makers and green building experts emerged as the professional groups providing the greatest number of recommendations, suggesting a broader range of ideas likely informed by their work experience. In contrast, architects and construction engineers provided comparatively fewer recommendations.



**Figure 4-12.** Technologies, software-aided simulation and modeling, building design principles, and approaches for green affordable housing design given by participants.

#### 4.2.6 Rating materials for green affordable housing design

After recommending materials, technologies, software, design principles, and approaches for green affordable housing design, participants were invited to rate ten examples of materials

provided in the interview. Figure 4-13 summarizes the ranking of 10 construction materials for green affordable housing design across four professional groups, using a scale from 1 (best choice) to 10 (least preferred).

Among architects, clay brick and bio-based materials received the most favourable assessment, each with a median ranking of 2.5, followed by recyclable materials (median = 3.5). Gypsum or plasterboard occupied a mid-range position (median = 5.5), alongside rammed earth (median = 5) and biocomposite material (median = 6). In contrast, precast concrete (median = 9), ceramic tile (median = 7.5), and natural stone (median = 7) were among the least preferred materials.

For construction engineers, recyclable materials were ranked most favourably (median = 1), followed by clay brick (median = 3) and biocomposite material (median = 4). Concrete block, rammed earth, and bio-based materials received similar mid-range rankings (median = 5.5). Higher median values were observed for precast concrete (median = 7.5), natural stone (median = 6), and ceramic tile (median = 8.5), indicating lower preference.

Green building experts demonstrated a strong preference for environmentally oriented materials. Bio-based material was ranked most favourably (median = 2.5), followed by clay brick (median = 4) and recyclable material (median = 4.5). Rammed earth and biocomposite material occupied mid-range position, both with a median ranking of 5. In contrast, precast concrete received a comparatively high median ranking (8), while ceramic tile and gypsum or plasterboard were also ranked toward the less-preferred end of the scale (both medians = 7.5). Natural stone showed a lower level of preference relative to environmentally oriented materials, with a median ranking of 6.5.

Among decision makers, recyclable material received the most favourable ranking (median = 2), followed by clay brick (median = 3) and bio-based materials (median = 4). Concrete block and precast concrete occupied intermediate positions (medians = 5.5 and 5, respectively). In contrast, natural stone (median = 8.5), gypsum or plasterboard (median = 8), and ceramic tile (median = 7.5) were among the least preferred materials.

Overall, median rankings varied across professional groups for several materials, highlighting both shared tendencies and professional differentiation. Three main materials emerge from this classification: clay brick, bio-based materials, and recyclable materials. Clay brick consistently exhibited favourable median values ranging from 2.5 to 4, although perceptions varied by professional background. Bio-based materials showed median rankings between 2.5 and 5.5, reflecting strong preference among architects and green building experts but more moderate evaluation by construction engineers. Recyclable materials are ranked in the third position and this is the preferred choice of construction engineers. Precast concrete displayed one of the widest ranges, with median rankings spanning from 5 to 9, indicating substantial divergence in perceived suitability across professional groups.

In contrast, recyclable materials were consistently ranked favourably across all professional groups, with median values ranging from 1 to 4.5, indicating a high level of cross-professional

consensus regarding their suitability. Ceramic tile consistently received higher median rankings (7.5–8.5), suggesting relatively low preference across all groups. Natural stone similarly showed generally high median rankings (6–8.5), although greater variability was observed between professional groups.



**Figure 4-13.** Ranking distribution of participants' rated materials for green affordable housing.

#### 4.2.7 Construction Cost and Sale Price

In the final part of Sections 3, 4, and 5, participants were asked to provide information on the current typical construction cost per square meter (m<sup>2</sup>), as well as the construction cost and sale price per m<sup>2</sup> for three types of buildings in Cambodia: affordable housing, green buildings, and green affordable housing. The objective of this section was to investigate these costs based on participants' knowledge, experience, and professional perspectives. The reported construction costs and sale prices were summarized using the median values for each participant group and building category. Table 4-9 presents these median values for all categories.

**Table 4-9.** Construction cost and sale price (by median value) per 1 m<sup>2</sup> of usual case, affordable housing, green building, and green affordable housing.

Group	Affordable housing	Green building	Green affordable housing

	<b>Usual construction cost (\$)</b>	Construction cost (\$)	Sale price (\$)	Construction cost (\$)	Sale price (\$)	Construction cost (\$)	Sale price (\$)
Arch	250	275	840.5	300	1,587	400	1,000
Eng	282.5	277.5	400	290	840	280	500
GB	350	300	700	600	1,150	350	850
DM	375	250	750	500	500	375	749.5

This section presents the results of the semi-structured interviews concerning construction cost and sale price per square meter of residential buildings as perceived by four professional groups: architects, construction engineers, green building experts, and decision makers. Participants were asked to report their estimates of the usual construction cost, and the construction cost and sale price of affordable housing (AH), green buildings (GB), and green affordable housing (GAH), all per built area of 1 m<sup>2</sup>. Figure 4-14 illustrates the distribution of responses across professional groups.

The results indicate noticeable variation among professional groups and building types. Median usual construction costs ranged from USD 250/m<sup>2</sup> among architects to USD 375/m<sup>2</sup> among decision makers. For affordable housing, median construction cost estimates were relatively similar across groups (USD 250 to 300/m<sup>2</sup>); however, median sale prices showed greater dispersion, with architects reporting the highest value (USD 840.5/m<sup>2</sup>) and construction engineers the lowest (USD 400/m<sup>2</sup>). In the case of green buildings, both median construction costs and median sale prices were substantially higher than those of affordable housing, particularly among green building experts and architects, who reported median construction costs of USD 600/m<sup>2</sup> and USD 300/m<sup>2</sup> and median sale prices of USD 1,150/m<sup>2</sup> and USD 1,587/m<sup>2</sup>, respectively.

For green affordable housing, median construction costs were generally lower than those of green buildings and, for most professional groups comparable to those of affordable housing, ranging from USD 280/m<sup>2</sup> to USD 400/m<sup>2</sup>. Architects constituted an exception, reporting a higher median construction cost for green affordable housing (USD 400/m<sup>2</sup>) compared to affordable housing (USD 275/m<sup>2</sup>) and green building (USD 300/m<sup>2</sup>). Median sale prices for green affordable housing were consistently higher than those of affordable housing across all groups, ranging from USD 500/m<sup>2</sup> to USD 1,000/m<sup>2</sup>. Overall, the findings indicate that participants perceived green buildings and green affordable housing to involve higher construction costs and sale prices than conventional or affordable housing, with the magnitude of these differences varying across professional groups.



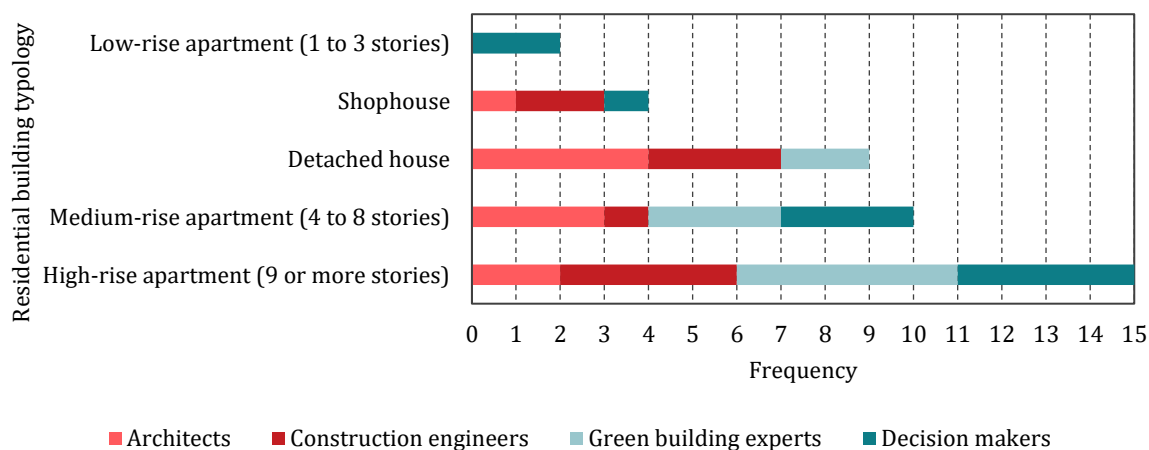
**Figure 4-14.** Building construction cost and sale price given by the participants.

#### 4.2.8 Preferred residential building typology for green affordable housing

In the last part of Section 4 of the interview, participants were asked to identify the residential typology they considered most appropriate for green affordable housing in the Cambodian construction sector. The objective of this question was to explore participants' perspectives and ideas regarding the type of green affordable housing they believed to be well adapted to, and suitable for construction within the context of the case study. This section presents the results of the analysis of green affordable housing residential typologies as perceived by four professional groups: architects, construction engineers, green building experts, and decision makers.

Figure 4-15 illustrates the frequency distribution of preferred green affordable housing typologies, including low-rise apartment (1 to 3 stories), shophouse, detached house, medium-rise apartment (4 to 8 stories), and high-rise apartment (9 or more stories). In response to the interview question regarding the most appropriate residential typology for green affordable housing in Cambodia, high-rise apartment was most frequently suggested overall, with green building experts reporting the highest frequency, followed by construction engineers and decision makers at equal levels. This reflects a strong perceived suitability of high-density residential development across these professional groups. Medium-rise apartment was also commonly proposed; however, responses were evenly distributed among architects, green building experts, and decision makers, while construction engineers reported this typology less frequently. Detached house was most frequently suggested by architects, followed by construction engineers,

with green building experts reporting slightly lower frequencies, indicating modest variation in perceptions of lower-density housing options. Shophouse was mentioned most often by construction engineers, whereas architects and decision makers reported similarly low frequencies. Low-rise apartment was the least frequently suggested typology and were mentioned only by decision makers. Overall, the findings indicate a general professional preference for medium- to high-rise residential typologies for green affordable housing in Cambodia.



**Figure 4-15.** Green affordable housing residential typologies recommended by the participants.

#### 4.2.9 Examples of affordable housing and green building in Cambodia

In Section 5 of the interview, participants were asked to provide examples of affordable housing and green residential buildings in Cambodia. The objective of this section was to investigate and learn from existing building projects, as participants are experienced professionals with in-depth knowledge of the construction sector. Additionally, this section aimed to identify the affordable housing projects most recognized by construction professionals.

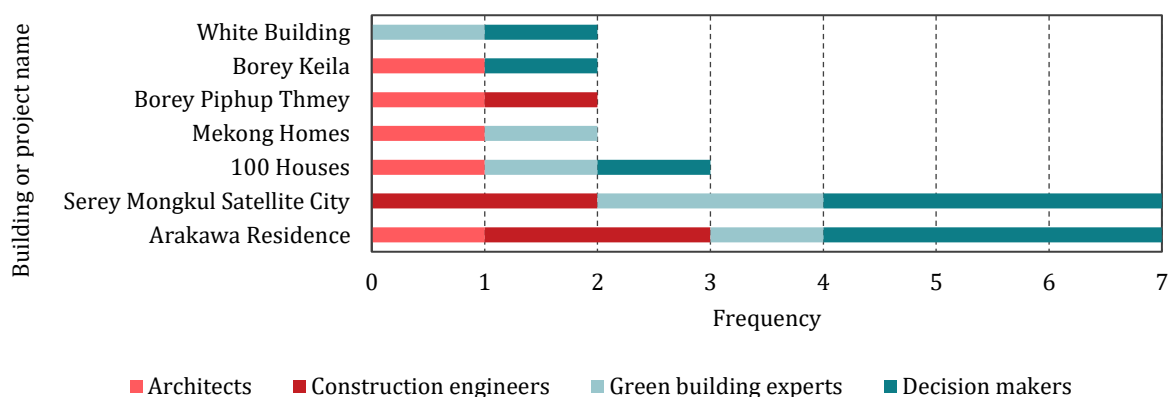
Table 4-10 summarizes the affordable housing projects mentioned by participants across professional groups. The reported frequencies represent the number of participants who referenced each project during the interviews. Note that the total frequencies do not equal the total number of participants (40), as some participants were unable to provide examples of either affordable housing or green residential buildings. Some of the provided information was incomplete or general, and in a few cases, participants mentioned nonexistent buildings. These entries were excluded from the analysis. Projects primarily functioning as hospitality or resort buildings, rather than residential housing, were also excluded from the results.

**Table 4-10.** *Affordable housing projects identified by participants.*

<b>Building or project</b>	<b>Arch</b>	<b>Eng</b>	<b>GB</b>	<b>DM</b>	<b>Frequencies</b>
Arakawa Residence	1	2	1	3	7
Serey Mongkul Satellite City	0	2	2	3	7
100 Houses	1	0	1	1	3
Mekong Homes	1	0	1	0	2
Borey Piphup Thmey	1	1	0	0	2
Borey Keila	1	0	0	1	2
White Building	0	0	1	1	2
Olympia City Phnom Penh	1	0	0	0	1
Bakong Village	1	0	0	0	1
Cambodian wooden house	1	0	0	0	1
Courtyard House project	0	1	0	0	1
Borey KP Morn Dany	0	1	0	0	1
Borey Samraong Village	0	0	1	0	1

Figure 4-16 illustrates the frequency with which specific affordable housing projects were identified by participants across professional groups. Only projects mentioned by at least two participants are shown in the figure. Participants identified a limited number of affordable housing projects in Cambodia, with recognition concentrated around a small set of developments. Arakawa Residence and Serey Mongkul Satellite City were the most frequently cited examples, each mentioned by seven participants across all four professional groups. Decision makers showed the highest level of recognition for these two projects (three mentions each), followed by construction engineers and green building experts, indicating stronger awareness of large-scale or policy-relevant housing developments among this group. The state of the art of these two projects is also discussed in Section 2.4.2 of the Literature review chapter, including their construction land size, main materials used, and price per housing unit. These projects are considered among the most significant housing developments in the country, having delivered thousands of houses and apartment units at prices comparable to other local affordable housing projects.

Other projects were mentioned far less frequently. 100 Houses was cited by three participants from three different professional backgrounds, while Mekong Homes, Borey Piphup Thmey, Borey Keila, and White Building were each mentioned twice. The 100 Houses project has been identified as a notable example of climate-responsive design and adaptation to vernacular architecture, reflected in both its design principles and the use of local materials. It was designed by the renowned Cambodian architect Molyvann VANN during the New Khmer Architecture era. Besides the 100 Houses, these projects were typically identified by only one or two professional groups, suggesting more fragmented or profession-specific knowledge. Overall, the results suggest that awareness of affordable housing in Cambodia is concentrated on a small number of prominent projects, while knowledge of other initiatives remains dispersed and uneven across professional groups.



**Figure 4-16.** Frequency of affordable housing projects identified by participants across professional groups.

Table 4-11 summarizes the green residential building projects identified by participants across professional groups. Figure 4-17 further illustrates the relative prominence of these projects based on total frequencies. As shown in the table, a wide range of green residential projects was identified, with a total of 20 buildings or project examples; however, most were mentioned by only one participant. Rose Apple Square was the most frequently cited residential project and was recommended by almost all participant groups, except architects. The project is designed to provide shared spaces and good accessibility for users, incorporate climate-responsive and vernacular design principles, maintain environmental quality, ensure a balance between urban and rural contexts, and enhance the value of both natural and cultural resources (Architizer, 2026). These characteristics are highly relevant and valuable for green residential building development.

**Table 4-11.** Green residential building projects identified by participants.

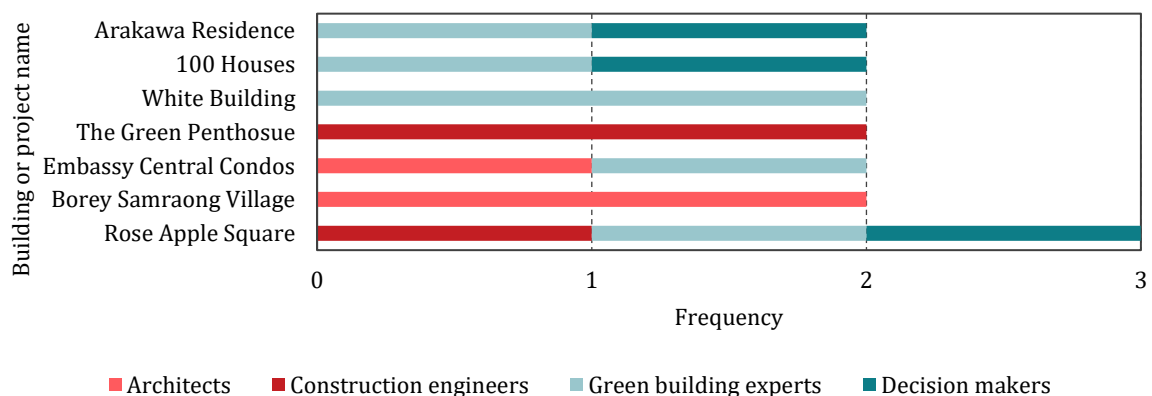
Building or project	Arch	Eng	GB	DM	Frequencies
Rose Apple Square	0	1	1	1	3
Borey Samraong Village	2	0	0	0	2
Embassy Central Condos	1	0	1	0	2
The Green Penthosue	0	2	0	0	2
White Building	0	0	2	0	2
100 Houses	0	0	1	1	2
Arakawa Residence	0	0	1	1	2
Bakong Village	1	0	0	0	1
Small Houses	1	0	0	0	1
Courtyard Box House	1	0	0	0	1
Urban Village	1	0	0	0	1
The Eco Residence Sen Sok	0	1	0	0	1
The Breeze House	0	0	1	0	1
New Khmer Architecture apartment	0	0	1	0	1
Bodaiju Residences	0	0	1	0	1

Borey Chankiri	0	0	1	0	1
Cambodian wooden house	0	0	0	1	1
Odom Living	0	0	0	1	1
Tronum Home	0	0	0	1	1
Serey Mongkul Satellite City	0	0	0	1	1

Figure 4-17 presents green residential building examples identified by participants, showing only projects mentioned by at least two participants. Overall, recognition of green residential buildings was limited, with no single project achieving broad consensus across professional groups. Rose Apple Square was the most frequently cited example, mentioned by three participants from three different professional backgrounds, including construction engineers, green building experts, and decision makers. This suggests that the project is perceived as a green residential development across multiple professional perspectives.

Several projects were mentioned twice, indicating moderate recognition. These included Borey Samraong Village, Embassy Central Condos, The Green Penthouse, White Building, 100 Houses, and Arakawa Residence. Notably, these projects were typically cited by participants from one or two professional groups only. For example, White Building was identified exclusively by green building experts, while Borey Samraong Village and The Green Penthouse was mentioned only by architects and construction engineers, respectively. In contrast, 100 Houses and Arakawa Residence were recognised by both green building experts and decision makers, suggesting some overlap in perceptions between sustainability-oriented and policy-oriented professionals.

Overall, the distribution shown in the figure indicates that awareness of green residential buildings in Cambodia is fragmented and profession-specific, with limited shared recognition across all professional groups. This pattern suggests the absence of widely recognized green residential exemplars and points to differing professional interpretations of what constitutes a “green” residential building.



**Figure 4-17.** Frequency of green residential building examples identified by participants across professional groups.

Overall, the results indicate a limited overlap between residential projects perceived as affordable and those perceived as green (Table 4-12). Arakawa Residence and Serey Mongkul Satellite City were most frequently recognized as affordable housing projects, each receiving seven mentions, yet they were infrequently identified as green residential buildings, with only two and one mentions respectively. In contrast, 100 Houses and White Building demonstrated a more balanced recognition across both affordability and environmental sustainability, although at lower overall frequencies. Other projects including Borey Samraong Village, Bakong Village, and the Cambodian wooden house were mentioned only once or twice in relation to both attributes, indicating minimal shared recognition. Collectively, these findings suggest that affordability and environmental sustainability are largely perceived as separate attributes within Cambodia’s residential developments, with very few projects consistently associated with both. Below are a few highlights of quotes from the participants that cited few projects where affordability and green design were considered together.

*“Arakawa Residence can be considered as both affordable housing and green building.”  
(Participant DM34)*




*“100 Houses is a good example of an affordable housing project dating back to the 1960s. When we consider the climate-responsive design of these buildings, they clearly also represent green building design.” (Participant DM37)*

**Table 4-12.** *Projects identified as both affordable and green by participants.*

<b>Building or project</b>	<b>Mentioned as affordable</b>	<b>Mentioned as green</b>
Arakawa Residence	7	2
Serey Mongkul Satellite City	7	1
100 Houses	3	2
White Building	2	2
Borey Samraong Village	1	2
Bakong Village	1	1
Cambodian wooden house	1	1
Rose Apple Square	0	3

Moreover, the eight project examples in the country identified as both affordable and green from participants’ responses are presented in more detail in Table 4-13, along with several key pieces of information. All projects are located mainly in Phnom Penh, the capital city, and other major provinces across the country. These projects vary in design and construction techniques across different periods, including traditional development, contemporary development, and the New Khmer Architecture era. The main materials used include reinforced concrete, tiles, masonry brick, glass, and wood. In terms of design principles, most projects focus on promoting natural ventilation and daylighting (climate-responsive design) and vernacular architecture (particularly in detached wooden house typologies), while incorporating fewer specific technological solutions.

**Table 4-13.** List of project examples identified by participants as both affordable and green, along with key project information.

<b>Arakawa Residence</b>	
	<ul style="list-style-type: none"> <li>• Architect: Arakawa Co., Ltd</li> <li>• Construction year: 2017</li> <li>• Localization: HV6J+755, St. (23), Phnom Penh 120802</li> <li>• Number of dwellings: 1,344</li> <li>• Main materials: RC concrete, glass, tile, masonry brick</li> <li>• Main design principles and technologies: promoting natural ventilation and light, central circulation for promoting air flow ventilation, fire alarm, smoke detector, and fire withstand doors</li> <li>• Access source: Realestate.com.kh</li> </ul>
<b>Serey Mongkul Satellite City</b>	
	<ul style="list-style-type: none"> <li>• Architect: WorldBridge Homes Co., Ltd</li> <li>• Construction year: 2021</li> <li>• Localization: Koh Kor Village, Sangkat Roka Khpos, Takhmao City, Kandal Province</li> <li>• Number of dwellings: 2,457</li> <li>• Main materials: RC concrete, masonry concrete, glass, ceramic and clay tile</li> <li>• Main design principles and technologies: using low-cost materials, minimal design</li> <li>• Access source: Habor Property Co., Ltd. website</li> </ul>
<b>100 Houses</b>	
	<ul style="list-style-type: none"> <li>• Architect: Molyvann VANN</li> <li>• Construction year: 1967</li> <li>• Localization: Sangkat Tuek Thla, Phnom Penh 120802</li> <li>• Number of dwellings: 100</li> <li>• Main materials: RC concrete, wood, clay tile, metal, masonry brick</li> <li>• Main design principles and technologies: climate-responsive design and vernacular architecture</li> <li>• Access source: Living ASEAN website</li> </ul>

### White Building (demolished)



- Architect: Ban Hap LU and Vladimir BODIANSKY
- Construction year: 1963
- Localization: 124 Samdach Sothearos Blvd (3), Phnom Penh
- Number of dwellings: 468
- Main materials: RC concrete, ceramic tiles, masonry brick
- Main design principles and technologies: climate-responsive design
- Access source: [Whitebuilding.org](http://Whitebuilding.org)

### Borey Samraong Village





- Architect: Bernhard Aerne (Aerne Architect & Associates)
- Construction year: 2022
- Localization: Along National Road 5, Prek Pnov, Phnom Penh
- Number of dwellings: N/A
- Main materials: RC concrete, masonry brick, glass, steel
- Main design principles and technologies: emphasis on natural light, cross-ventilation, and "dual orientation" (houses having both a front and a private backyard)
- Access source: [Aernearchitect.org](http://Aernearchitect.org)

### Bakong Village



- Architect: Aerne Architects & Associates
- Construction year: 2019
- Localization: 9WGW+9FQ, Rd Number 60, Krong Siem Reap
- Number of dwellings: 317
- Main materials: RC Concrete, masonry brick, glass, steel
- Main design principles and technologies: focusing on cross-ventilation, natural light, a balance

	<p>between community and privacy, sky-wells, and open façades</p> <ul style="list-style-type: none"> <li>• Access source: ERA Cambodia</li> </ul>
<b>Cambodian wooden house (example)</b>	
	<ul style="list-style-type: none"> <li>• Architect: Okhna Roeung BUN</li> <li>• Construction year: 1920</li> <li>• Localization: Battambang province</li> <li>• Number of dwellings: 1</li> <li>• Main materials: hardwood, clay tile, thatch</li> <li>• Main design principles and technologies: vernacular architecture</li> <li>• Access source: Genevieve Fields website</li> </ul>
<b>Rose Apple Square</b>	
	<ul style="list-style-type: none"> <li>• Architect: ReEdge Architecture</li> <li>• Construction year: 2024</li> <li>• Localization: Sok San Road/Rose Apple Road, Siem Reap province</li> <li>• Number of dwellings: 207</li> <li>• Main materials: concrete, steel, glass</li> <li>• Main design principles and technologies: design maximizing natural light and airflow, high-quality finishes, energy-efficient systems, and smart layouts</li> <li>• Access source: Architizer.com</li> </ul>

#### 4.2.10 Discussion on affordable housing and green building sector in Cambodia

In this section, the findings of this chapter are briefly discussed, with affordable housing as the primary topic guiding this research. The findings show that construction professionals in Cambodia provide diverse definitions of affordable housing, with some offering detailed recommendations and requirements that should be considered in the development of affordable housing projects in the country. Affordable price, enhanced quality of life, comfort, housing for all, housing for low- to middle-income people, and security were identified as the most commonly recognized and defined characteristics among construction professionals in Cambodia. All these buildings as well as Rose Apple Square, which received 3 votes as green building, will be analyzed in the Discussion chapter.

When related to architectural design and construction techniques, location, materials choice, energy consumption, and accessibility to public service and facility, participants specified criteria and guidance are the most important, based on the results in Table 4-4. One particular response covered almost all of the findings. Participant Arch3 mentioned that affordable housing principles include accessibility to materials and public services, acceptable construction and purchase

prices, belief and cultural considerations embedded in vernacular architecture, avoidance of risky locations, and enhancement of the economy of living. Given that this participant has worked in slum community upgrading and affordable housing construction for approximately 25 years, they demonstrate a strong understanding of the field and study context.

However, the term “housing for all” as a definition of affordable housing in Cambodia is not entirely appropriate due to its global and generalized nature. Instead, the term “housing for poor and low- to middle-income people” is more relevant, as supported by previous studies by Seng (2020) and Kol et al. (2022) in the same context (Kol & Brugman, 2022; Seng, 2020). Therefore, the results suggest that the definitions, recommendations, and criteria identified in this study can serve as baseline standards and provisions for future affordable housing projects in Cambodia. These definitions and characteristics may also be recognized and adopted by other construction professionals and relevant sectors in the country.

During the interviews, participants also defined and described green building design based on their own understanding, experience, and knowledge. They presented principles, strategies, and technologies related to green building practices adapted to the Cambodian construction sector, rather than strictly following established definitions or theories. Participants generally agreed that green building design in Cambodia cannot follow all global green building principles from A to Z. Instead, they implement green building concepts in their projects when and where feasible.

Ragheb et al. (2016) summarized five major elements of green building design: sustainable site design, water conservation and quality, energy and environment, indoor environmental quality, and conservation of materials and resources (Ragheb et al., 2016). Participants in this study shared many elements aligned with these principles (saving energy, water, and materials) and indoor environment quality, with a focus on promoting natural lighting, ventilation, and cooling, while also proposing additional context-specific characteristics, such as other resources savings (cost, land use, and maintenance), flood-resilient design, cultural consideration, and bioclimatic design. Some participants also discussed site and surrounding integration, which relates to sustainable site design. Regarding energy and environment, participants emphasized minimizing environmental impacts and integrating renewable energy into green building design.

However, several misunderstandings regarding green buildings in Cambodia were identified during the survey, particularly concerning building typology. Some participants believed that green buildings should only be high-rise buildings. This perception may stem from the fact that a limited number of high-rise buildings in Cambodia have received green building certification, leading participants to associate green building objectives exclusively with this typology.

The discussion on green affordable housing in Cambodia’s construction sector generated diverse perspectives among participants. Many attempted to identify a balance between affordability and green building principles. Initially, some participants found it challenging to respond, as they perceived green building design to be costly, while affordable housing must be low-cost. Conversely, other participants argued that green building does not necessarily increase costs, as

green affordable housing can be developed using local resources and traditional practices, such as Khmer traditional housing prototypes.

The most feasible and contextually appropriate principles for green affordable housing identified in this study relate to architectural design and construction techniques, material selection, bioclimatic design, quality of life, resource efficiency, greenery, affordability, minimized environmental impact, renewable energy, rainwater harvesting, waste management, and reduced construction costs. Regarding material recommendations, participants identified the top materials as wood, concrete, clay, bamboo, earth, and lightweight concrete. However, some participants were unable to specify particular materials and instead referred to general material types or alternatives such as local materials or recycled materials.

The 2017 Policy on Incentives and the Establishment of a National Program for the Development of Affordable Housing in Cambodia introduced measures to encourage developers to construct dwellings priced between USD 15,000 and USD 30,000 (GGGI et al., 2022). An example of affordable housing technical standards provided by the General Department of Housing under the Ministry of Land Management, Urban Planning, and Construction (MLMUPC) includes a residential prototype with a dwelling floor area of approximately 26 m<sup>2</sup> in the form of a shophouse (General Department of Housing/MLMUPC, 2025). Existing dwellings in affordable housing projects in Cambodia show sale prices ranging from USD 25,000 to USD 38,888 for Serey Mongkul Satellite City (28 m<sup>2</sup>) and USD 28,500 to USD 31,800 for Arakawa Residence (22-54 m<sup>2</sup>). However, the Arakawa Residence project set a sale price of USD 1,400 per m<sup>2</sup>, which is higher than the prices found in this study.

The sale price of green affordable housing identified in this study, ranging from USD 13,000 to USD 26,000 for a 26 m<sup>2</sup> unit, aligns with the price range suggested by the National Policy. Based on the construction cost identified in the study (USD 280-400 per m<sup>2</sup>), green affordable housing can be developed in line with the National Program. However, developers may face challenges due to limited profit margins. Floor area plays a critical role in affordable housing; if not carefully controlled, it can significantly affect construction costs and sale prices. Therefore, government intervention and support from non-governmental organizations are necessary to ensure the provision of green affordable housing at accessible price levels and to promote sustainable housing development.

Regarding residential building typologies, high-rise apartments were the most frequently recommended by construction professionals, followed by medium-rise apartments and detached houses. Approximately three-quarters of participants recommended high-rise buildings, one-third suggested medium- and low-rise buildings, and one-quarter proposed single-family houses. These findings indicate that multiple residential typologies can be suitable for green affordable housing. Currently, affordable housing projects in Phnom Penh are being developed as high-rise apartment buildings (20–24 stories), such as Arakawa Residence, which has 21 floors, while other projects consist of shophouses or terraced housing. Detached houses are generally not considered ideal due to high urban land prices and their land consumption per built area. Consequently, high-

risers and medium-rise apartment buildings and shophouses can be identified as the three residential typologies recommended for green affordable housing in Cambodia's capital city.

Several limitations of this study should be acknowledged. First, some professional profiles within the construction sector were not included, particularly mechanical, electrical, and plumbing (MEP) engineers, as well as housing occupants. Conducting interviews with construction professionals, which required approximately 30 minutes each, proved challenging, especially when contacting individuals in senior positions, often requiring multiple follow-ups. Although the number of participants was sufficient for qualitative analysis, consistent with literature suggesting a minimum of 5 to 50 experts (Dworkin, 2012), including more participants from similar professional backgrounds could have provided additional insights. Occupants were excluded because the study focused on construction professionals rather than building users. Future research should include occupants to test and validate users' perceptions related to the identified characteristics of green affordable housing.

Future research should also focus on practical approaches to developing green affordable housing projects with broader stakeholder engagement. Initial efforts could prioritize construction cost and sale price analysis through consultation with key stakeholders in the affordable housing sector to determine pricing strategies that meet green building requirements while remaining affordable for low- to middle-income households.

Overall, the definitions and characteristics identified in this study provide a foundation for future research and can support the development of guidelines and regulations for green affordable housing projects in Cambodia.

### 4.3 CHAPTER CONCLUSION

This research, developed based on interviews addressing the integration of green building design and affordable housing in Cambodia's construction sector, received significant interest from participating construction professionals. This interest reflects the limited number of existing studies in the fields of architecture and sustainable building construction within the Cambodian context. Drawing on participants' perspectives, experience, and current professional practices, this research identifies and characterizes the key attributes that affordable housing, green buildings, and integrated green affordable housing should incorporate into their design.

The construction of green affordable housing in Cambodia should consider the following key aspects:

- 1) architectural design and construction techniques, including community and common spaces, application of green and sustainable design principles, minimal design and decoration, adherence to standards, space optimization, building quality, and accessibility;
- 2) material selection, emphasizing local, reused, recycled, recyclable, affordable, natural, eco-friendly, and green-labeled materials;

- 3) bioclimatic design;
- 4) enhancement of quality of life through human comfort, social and community relationships, appropriate living spaces, healthy and environmentally friendly indoor environment, recreational opportunities, and improved lifestyles;
- 5) resources and cost efficiency;
- 6) integration of greenery;
- 7) maintaining affordability to the greatest extent possible;
- 8) minimization of environmental impacts;
- 9) integration of renewable energy;
- 10) rainwater harvesting;
- 11) waste management; and
- 12) minimization of construction costs.

The construction cost of green affordable housing should range from USD 280 to USD 400 per square meter of built area. The sale price identified in this study ranges from USD 13,000 to USD 26,000 for a housing unit with a floor area of 26 m<sup>2</sup>. High-rise apartment buildings were identified as the preferred building typology for green affordable housing in the capital city, although medium- and low-rise apartment buildings and shophouses were also considered suitable alternatives.

The results of this research provide feasible and contextually adapted principles and criteria for integrating green residential design with affordable housing in Cambodia. These findings may support stakeholders in the construction sector by offering guidance for future research and practical applications related to green and affordable housing development. The identified characteristics and considerations can be utilized by architects, civil and construction engineers, green building designers, residential developers, and policymakers. These findings contribute valuable insights and guidance for future research, particularly studies aiming to develop approaches and strategies for green housing and sustainable building practices.

This chapter identifies the key characteristics and significant parameters of affordable housing, green building design, and their integration, as well as the level of awareness among construction professionals. Next chapters will analyze the environmental performances of existing recent buildings in Cambodia, through life cycle analysis.

# 5

## Life cycle assessment of a townhouse in Cambodia

This chapter introduces the application of life cycle assessment (LCA) to residential buildings in Cambodia, a developing country in tropical Southeast Asia. First, relevant literature on sustainable building practices, building LCA studies in similar contexts, and carbon-reduction strategies is reviewed. A townhouse is then selected as the case study and assessed following ISO LCA standards and a structured methodological framework, modeling with SimaPro software and the ecoinvent 3 database. Life cycle impact assessment is conducted using the Environmental Footprint (EF) 3.0 method. Strategies to reduce carbon emissions and environmental impacts across building life-cycle stages are proposed and evaluated. Finally, the carbon footprint and other relevant impact categories of a Cambodian residential building are quantified and analyzed across life-cycle stages and improvement scenarios.

## 5.1 LIFE CYCLE APPROACH TO SUSTAINABLE BUILDING

The construction sector is a vital role in urbanization and economic growth and also a major contributor to global carbon emissions (Gardezi et al., 2021). In China, it accounts for approximately 25% of national carbon emissions, while in Singapore it contributes about 16% of total emissions, ranking as the third-largest emitting sector. In Cambodia, where the construction sector is rapidly expanding, buildings accounted for 52% of national energy consumption in 2019 (National Committee on Energy Efficiency, 2022). Despite this growth, sustainable building practices and awareness remain limited within the current construction boom, particularly in the capital city, Phnom Penh, posing a significant challenge to the sector (Waibel, 2017). Consequently, GHG emissions from buildings are expected to increase, raising concerns for environmental sustainability. Given the strong link between construction activities and carbon emissions, reducing the environmental impacts of newly constructed residential buildings is critical for achieving national sustainability objectives and aligns with Cambodia's target of reducing residential building energy consumption by 34% by 2030.

The paradigm shifts toward creating a more sustainable built environment in the region of Southeast Asia is becoming a key issue and it requires the participation of all stakeholders, and strategies to encourage its implementation (Jayawardana et al., 2023; Shafii et al., 2005). Specific sustainable construction guidelines and principles remain underdeveloped in Cambodia due to limited awareness and knowledge, as well as an unwillingness to adopt new sustainable technologies (Durdyev et al., 2018). Sustainable architecture has not yet been sufficiently studied within the Cambodian context and only a limited number of studies provide a basic overview of sustainable design practices (Taing et al., 2025). Addressing this research gap is crucial for advancing green building initiatives, particularly low-carbon buildings in Cambodia from a life cycle perspective.

In the field of building sustainability assessment, researchers have introduced new methods and green technologies to minimize the environmental impacts of the building sector and promote green building design. One of these innovative methodologies is the life cycle assessment (LCA) of buildings, which estimates the environmental impacts generated by a building throughout its whole life cycle (Fava et al., 2009). LCA was defined simply as a method of environmental accounting that tracks inputs from nature and outputs to nature considering all processes in the manufacture, use, and disposal of a product or system (Simonen, 2014).

The ISO 14040 describes principles and framework of LCA and ISO 14044 describes the requirements and guidelines (ISO, 2006a, 2006b). The European standard EN 15978 is designed for building LCA study (El khouli et al., 2015; European Committee for Standardization, 2012). Architects and planning professionals recognized LCA in supporting the decision-making process in building design (Mateus et al., 2011). While the literature on building LCA has expanded in recent years, quantitative information on the carbon footprint and environmental impacts of buildings remains limited for many developing countries. Previous studies by Ansah et al. (2023) and Nawarathna et al. (2021) identify substantial gaps in LCA research and embodied carbon

assessment for buildings in these contexts (Ansah et al., 2023; Nawarathna et al., 2021). The application of LCA to buildings requires extensive data and informed methodological choices (Fnais et al., 2022). Consequently, although building LCA methodologies are well established in many developed countries, their application remains limited in developing regions, particularly in South America, Southeast Asia, and Africa (Jayawardana et al., 2023b; Ortiz-Rodríguez et al., 2010). Embodied carbon emissions from buildings in developing countries represent a non-negligible component of life-cycle impacts and warrant systematic assessment (Nawarathna et al., 2021). Immediate action is needed to reduce embodied carbon emissions and circular economy concepts also need to be implemented (De Silva et al., 2023). Responding to the growth of urban residential buildings in Southeast Asia, it is crucial to reduce carbon emissions and assess energy use and emissions in the building sector of Southeast Asia (Zhang et al., 2019).

## 5.2 BUILDING LCA STUDIES IN SOUTHEAST ASIA

In recent years, LCA has been developed and assessed broadly for several types of buildings and facilities. A general literature review of residential buildings LCA in Southeast Asia in the last decade was made to understand the goals, assessment indicators, life cycles included, and depth of study. In total, 16 peer-reviewed studies on building life cycle assessment published up to 2023 were selected, of which 10 focus on residential buildings (Abd Rashid et al., 2017; Arceo et al., 2023; Gardezi et al., 2021; Iqbal et al., 2017; Jia Wen et al., 2015; Ong et al., 2013; Salzer et al., 2017; Surahman et al., 2016; Wan Omar, 2018; Zuraida et al., 2019). It was found that 4 papers concluded cradle-to-grave to assess building environmental impact (Abd Rashid et al., 2017; Iqbal et al., 2017; Tevis et al., 2019; Tulevech et al., 2018) and 6 out of the 16 papers evaluated only the GWP (Koiwanit et al., 2021; Ong et al., 2013; Rashid et al., 2017; Salzer et al., 2017; Tevis et al., 2019; Tulevech et al., 2018). To our knowledge, no article assesses the environmental impacts of a house in Southeast Asia based on the sixteen impact categories of the Environmental Footprint (EF) 3.0 method. Thus, LCA studies aimed to assess carbon footprint or GWP and environmental impacts, as well as implementing LCA of design strategies in Southeast Asia, address a research gap in the region and advance the application of LCA in the building sector in developing countries.

LCA practice in Cambodia has only recently emerged and has been applied primarily in sectors such as hydropower development, material production, and food systems (Chea et al., 2022; Chhun et al., 2021; Hor et al., 2021). Despite this progress, the application of LCA to buildings remains largely absent from the existing literature. In particular, studies addressing building-scale environmental impacts in Cambodia are limited by the lack of localized life cycle inventory (LCI) data for construction materials, energy, and associated emission factors. Recent initiatives, including the low-carbon building project led by the Global Green Growth Institute (GGGI), indicate growing interest in applying LCA principles to the building sector (GGGI, 2025). However, reported practices remain restricted to selected life cycle stages, mainly material production stage and operational energy use. Furthermore, the emission factors and environmental product declarations (EPDs) adopted in these initiatives are sourced from global databases, European

datasets, and selected Southeast Asian countries, rather than from Cambodia-specific inventories. Due to the absence of detailed building case studies, LCI data are commonly adopted from the literature.

The reviewed studies and initiatives collectively highlight two critical challenges for building LCA in Cambodia: 1) the absence of locally representative material and energy inventory data, and 2) the limited consideration of complete building life cycle stages. These gaps in the literature underscore the need for adaptable LCA methodologies capable of operating under data-scarce conditions, while maintaining transparency and consistency with international standards.

### 5.3 INTEGRATED STRATEGIES FOR EMBODIED AND OPERATIONAL CARBON REDUCTION

The LCA of an office building in Sri Lanka revealed that prefabricated components contribute to GHG emission savings of 8.06% (Jayawardana et al., 2023b). Furthermore, Tavares et al. (2022) found that lightweight prefabricated buildings can have lower embodied impacts than heavyweight conventional buildings (Tavares et al., 2022). According to these studies, prefabricated materials generate lower building environmental impact and can be chosen as efficient design strategy for buildings, as defined by LCA. Moreover, building elements such as the substructure, frame, floors, and external walls were identified as carbon-significant elements in the study by Nawarathna et al. (2021). Thus, material strategies associated with these elements combined with the study of their impact assessments have the potential to reduce the embodied carbon of buildings. Material selection for a building's structure is also crucial for reducing impacts throughout the building's lifespan (Rodríguez et al., 2023).

Durdyev et al. (2018) emphasized that efforts toward sustainable construction in Cambodia should prioritize the selection of durable materials and the minimization of material consumption (Durdyev et al., 2018). A residential project in Vietnam (Figure 5-1, left) exemplifies this approach by reducing unnecessary architectural elements, including the removal of finishing layers and the reduction of non-essential walls and doors, in order to lower construction costs (Tropical Space, 2019). Baked brick was used throughout the house because it is a widely available and low-cost local material. In addition, its hygroscopic properties contribute to indoor humidity regulation. A similar design strategy can be observed in a dormitory building in Cambodia (Figure 5-1, right), which was constructed based on sustainability principles (Rethinking The Future, 2024). The building envelope incorporates bamboo, a locally sourced material, as a form of solar protection. A minimalist design approach was applied to both the overall building and its components, ensuring that materials were used only where functionally necessary. For instance, some walls were left unpainted, and certain surfaces were finished without tiles, thereby reducing material use and construction complexity.



**Figure 5-1.** Left: tertiary house in Vietnam (*Tropical Space*, 2019) and right: dormitory in Cambodia (*Rethinking The Future*, 2024).

Within the tropical Southeast Asian context of Cambodia, timber or wooden houses are commonly recommended, as they align with local cultural preferences and embody principles of vernacular architecture as shown in Figure 5-2, left (Che-Ani et al., 2008; Grow, 2011). The timber structure strategy reflects the vernacular architecture of traditional local wooden houses that are built off the ground and which are made of a wooden structure with a roofing from clay tile. Timber accounts for very low CO<sub>2</sub> emission according to its requiring minimal energy input for the manufacturing process (Premrov et al., 2021). Given that the materials production contributes mainly to the environmental impact, selecting eco-friendly materials for innovative walls instead of the conventional cement and brick walls, can promote more sustainable construction (Meireles et al., 2024). Lean manufacturing is known as a method of maximizing productivity, reducing overall construction times, and minimizing wasteful activities in construction (Jayawardana et al., 2023). This can lead to reduced operational losses and promoting a low carbon strategy.



**Figure 5-2.** Left: Cambodian wooden house represented vernacular architecture (*The Gentry Hub*, 2022) and right: household rooftop solar panels in Phnom Penh city (*Globe Media Asia*, 2018).

The potential for using renewable energy sources in Southeast Asia is high but these green technologies provided only around 15% of the region's energy demand in 2022 (IEA, 2022). Solar energy is promoted to be a practicable renewable energy source, and it can take part in reducing

household electricity consumption. Nawarathna et al. (2021) introduced initiatives for carbon reduction in buildings in Sri Lanka, including promoting the generation of electricity from solar energy (Nawarathna et al., 2021). An LCA study of a NZEB in El Salvador, a developing country, highlighted the importance of using renewable energy as a building's energy source to offset impacts generated by other phases of the life cycle (Rodríguez et al., 2023). In Cambodia, solar photovoltaic (PV) lighting products have a lower environmental impact than conventional lighting (Durlinger et al., 2012). Their impact is either lower or comparable to that of lighting products powered by grid electricity. The location of the studied house receives sunshine throughout the entire year averaging 6 to 8 hours per day and producing daily averages of 5 kWh/m<sup>2</sup> (Phnom Penh Real Estate, 2021), to maximum 5.6 kWh/m<sup>2</sup> (United Nations Development Programme, 2019). This condition allows the country to start solar energy plants in several regions. Figure 5-2 (right) illustrates an example of rooftop solar panels installed on a house in Phnom Penh.

Green building design is the practice of creating more resource-efficient comfortable buildings. The literature review highlights different types of green building strategies related to the building context: passive design strategies (no cooling, solar protection, rational use of building materials, etc.), environmental production and construction modes (reused materials, recycled materials, prefabrication, etc.), use of bio-based materials, and improved energy systems (including renewable energy utilization).

Lai et al. (2023) present different building solutions for green building design in Southeast Asia (Lai et al., 2023), while Zhang et al. (2021) highlights the importance of using solar energy in green building design in Asia (Zhang et al., 2021). In Southeast Asia, installing solar protections on façade windows exposed to direct solar radiation has great advantages in reducing indoor temperature and cooling energy consumption (Lai et al., 2023). Green buildings use often recycled materials in tropical regions, because it allows saving construction costs (Shaikh et al., 2017). Traditionally, Cambodian residential buildings were built with low thermal mass materials and without wall insulation (Lai et al., 2023). Green roofs and shaded terraced roofs are effective strategies to improve the building thermal efficiency in Southeast Asia, while responding to space scarcity in urban areas (Sangkakool et al., 2018).

Nine countries in Southeast Asia have developed their own green building assessment tools. For Cambodia, it is the rating system Cambodia Energy and Environmental Leadership (NCSD/Ministry of Environment of Cambodia, 2021). The green building assessment tools in Southeast Asia mainly focus on better energy systems, such as efficient air-conditioning and lighting, improved building thermal performance and ventilation, renewable energy utilization, as well as high efficiency use of water (Lai et al., 2023).

Based on the literature review, the scenarios assessed in this study are defined as design strategies aimed at reducing environmental impacts. These scenarios were selected in accordance with recommendations from previous studies and observations of the existing building context. The selection process also considered the feasibility and potential benefits of adopting low-carbon building materials and on-site solar energy production in Cambodia. Accordingly, five strategies were defined to improve the environmental performance of the studied building: 1)

materials optimization; 2) the use of low-impact manufacturing processes and bio-based materials; 3) the adoption of lightweight timber structural systems; 4) on-site renewable electricity generation; and 5) a combined strategy integrating the four proposed approaches. These strategies are described in detail in the following sections.

## 5.4 LCA OF A TOWNHOUSE IN CAMBODIA

The objectives of the research are to perform LCA and to assess five design strategies to reduce the carbon footprint and environmental impacts of residential buildings in Cambodia. The analysis is based on the LCA of a case study: a townhouse in Phnom Penh and study their variability of results across different scenarios. Klöpffer et al. (2014) declared that an innovation in LCA case studies can be the first attempt to apply a life cycle study in a specific research field within a country still unaccustomed to the use of life cycle thinking (Klöpffer et al., 2014). UNEP/SETAC presents this type of innovation as having significant value for developing regional capacity and promoting the use of life cycle thinking throughout the world (UNEP/SETAC Life Cycle Initiative, 2013). This study is the first LCA of a building in Cambodia and the carbon footprint, environmental impacts, and best building design strategies aiming to reduce impacts for townhouses in Cambodia are unknown. Therefore, this research studying the LCA of building design strategies aimed at reducing environmental impacts is an innovative approach for informing the local construction sector and decision-makers, while also serving as a benchmark for future work. Moreover, the LCA results of the design strategies assessed in this study are considered novel, as they compare the potential for reducing carbon footprint and environmental impact, integrating the sixteen impact categories of the EF 3.0 method, which has rarely been achieved in world literature.

Moreover, this study aims to address a broader research gap: the lack of building LCA results in the context of developing countries (Ansah et al., 2023; Nawarathna et al., 2021; Ortiz-Rodríguez et al., 2010), and more particularly in Southeast Asia (Jayawardana et al., 2023), where no reference could be found on the sixteen environmental impacts of a house. The carbon footprint results of this study will be compared with seven other case studies of buildings in Southeast Asia and developing countries, as well as in tropical climate. The used methodology, results, discussion, and difficulties encountered in this study such as finding local data on the end of life stage of buildings in Cambodia, will help guide future research in the context of developing countries.

### 5.4.1 Selection of building case study

The selected building case study is a three-story townhouse, as shown in Figure 5-3, located in Sangkat Boeng Kak 1, Khan Tuol Kouk, Phnom Penh, Cambodia. The townhouse in this context is also defined and known as a shophouse or terraced house. The case study was selected based on this housing type is mostly built in urban areas, an important part of current city development and suitable for the Cambodian context (Pengly & Tirapas, 2022; Taing et al., 2023). The number of constructions of this townhouse type increased by more than 34% from 2020 to 2021 (Choun

et al., 2024). The construction method and materials are common, including reinforced concrete frames, brick masonry walls without insulation, and single-glazed windows and doors with metal frames. The specification of the building is given in Table 5-1 and the floor plans of the building are illustrated in Figure 5-4.



**Figure 5-3.** Street view of the townhouse (left) and interior views of the ground floor (top right) and first floor (bottom right).

**Table 5-1.** Specification of the building case study layout.

Building case study layout	Specification
Number of floors	3 floors
Number of inhabitants	10
Gross floor area [square meters (m <sup>2</sup> )]	157
Annual electricity consumption [kWh]	6,480
Structure	Reinforced concrete frames
Walls	Brick masonry without insulation
Foundation	Reinforced concrete and compacted soil
Roof	Hollow steel truss and corrugated zinc sheets
Doors and windows	Glass and aluminum
Finishing	Ceramic tiles, base plaster, and painting

The townhouse consists of a ground floor, a mezzanine floor, and a first floor (Figure 5-4). It was originally designed as a single-family dwelling, comprising a living room, kitchen, bedrooms,

toilets, and bathrooms. After being rented, the living room on the ground floor was repurposed as a beauty salon, and the rear portion of the first floor was converted into a kitchen.

The ground floor includes a living room at the entrance, one bedroom, a kitchen, a toilet and bathroom, a small storage area, and a staircase providing access to the mezzanine floor. The mezzanine floor contains one bedroom, a toilet, and a bathroom. These two floors are occupied by one family.

The first floor accommodates two bedrooms, a kitchen, and a bathroom and is occupied by a second family. Access to this floor is provided by an external staircase located adjacent to the ground-floor living room. The rooftop terrace is a shared space covered by a metal truss structure and is used for home gardening, clothes drying, and occasional social activities such as barbecues.



**Figure 5-4.** Floor plans of the townhouse.

## 5.5 RESEARCH METHODOLOGY

The research methodology adopted in this study is based on a mixed-methods approach, combining LCA in accordance with international standards and a comprehensive review of existing literature. The LCA of a townhouse in Cambodia was conducted in compliance with ISO 14040 and ISO 14044, following the four established phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006a, 2006b). Detailed descriptions of each phase are provided in the following sections.

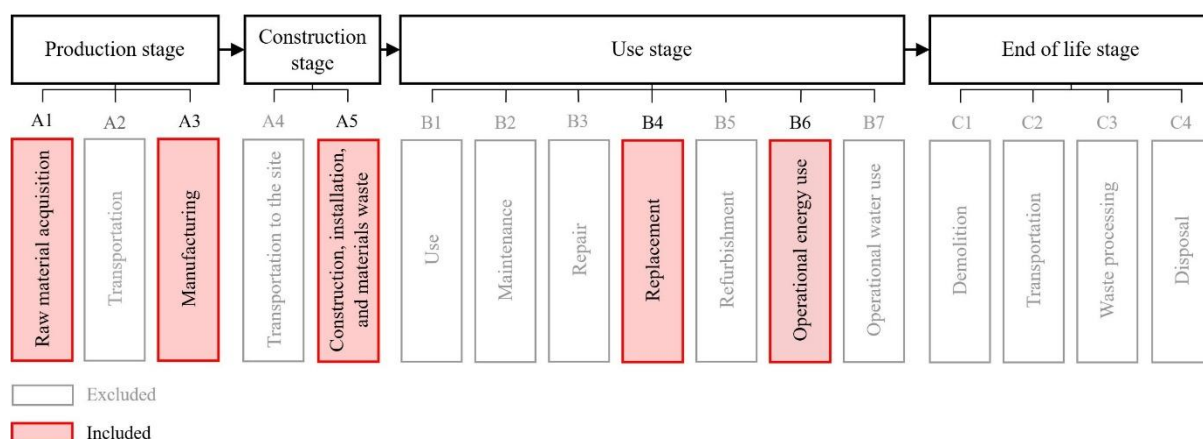
LCA modelling of all building components and energy use across the defined life cycle stages was performed using SimaPro software (version 9.4.0.2), with life cycle inventory data sourced from the ecoinvent database (version 3.8). The modelling included detailed inputs related to material production processes and energy types involved throughout the building life cycle. Ecoinvent is a widely recognized and internationally accepted database that provides comprehensive inventory data suitable for global LCA applications (Wernet et al., 2016). The cut-off system model was applied, and datasets representing Switzerland (CH) and Europe - regional average (RER) were

prioritized due to their higher data quality and transparency. Where CH and RER datasets were unavailable, datasets from Europe without Austria and the Rest of World (RoW) were used. Environmental impacts were assessed using the EF 3.0 impact assessment method, which includes sixteen impact categories (Mirzaie et al., 2020). This multi-impact approach enabled a comprehensive evaluation of the environmental performance of the studied building, rather than limiting the analysis to a single indicator such as global warming potential.

Defining building scenarios aimed at reducing the life cycle impacts of the studied building was then carried out. The concept of proposing these scenarios also has been explored in the works of Iyer-Raniga et al. (2012) and Lokko et al. (2024), which focus on building intervention strategies and low-carbon building materials for housing in Australia and Africa, respectively (Iyer-Raniga et al., 2012; Lokko et al., 2024). Finally, a comparison of the results of this study with those of other published researches was also considered, as recommended by Abd Rashid et al. (2017).

### 5.5.1 Goal and scope definition

The goal of the study is to evaluate sixteen environmental impacts including the carbon footprint and the overall environmental impacts of a townhouse in Cambodia. The system boundaries determine which process stages are considered in an LCA. The European Standard EN 15978 was used because it regarded the sustainability of construction works and defined four life cycle stages: production stage (A1-A3), construction stage (A4-A5), use stage (B1-B7), and end of life stage (C1-C4). Figure 5-5 illustrates stages that are considered in this study and stages that are related to materials use and operational energy use. The most relevant stages of the building life cycle, which are material production stage (A1 and A3), construction stage (A5), and use stage (B4 and B6) were included in the system boundaries. The end of life stage was not considered in this study because of a lack of data and information about building demolition, potential of recyclability of building materials, transportation, and disposal site. And while other sub-stages (A2 and A4) related to transportation type and distance are excluded due to there are no reliable information or reference justified in the local context. Activities and processes associated with the B1, B2, B3, and B5 sub-stages were not included in this case study. In addition, because the townhouse is occupied by two different households, monthly water bills were not systematically recorded in a single account, which made it impossible to obtain reliable data for operational water use (B7). Similar limitations are reported in published building LCA studies, which often include only selected life cycle stages. For example, studies in Malaysia focused on the material and construction and pre-use phases (Jia Wen et al., 2015b; Wan Omar, 2018), while research in Thailand considered mainly the operational stage (Koiwanit et al., 2021). Likewise, a study in Belgium included only the product, construction, and use stages (Decorte et al., 2021).



**Figure 5-5.** System boundaries of the building life cycle stages considered in the study following EN 15978.

Building carbon footprint is the amount of GHG produced throughout the life cycle of a building and the environmental footprint quantifies the overall environmental impacts based on different impact categories. The carbon footprint is calculated in kg CO<sub>2</sub>-eq/m<sup>2</sup> and the environmental footprint is calculated in level of single score in millipoints (mPt).

The functional unit of the study was estimated at one m<sup>2</sup> of gross floor area (GFA) of the building, and the residential building lifespan is set for 50 years as suggested in literature reviewing LCA in building industry (Abd Rashid et al., 2015). The 50-year building lifespan was adopted due to the absence of published Cambodian building regulations or documented local practice specifying an official service life for residential buildings (Skriabikova, 2022). Existing life cycle related reports in Cambodia apply widely varying lifespan assumptions, such as 100 years for hydropower infrastructure based on design documents and 25 years for the economic life of buildings (Chhun et al., 2021; IPS Cambodia, 2017), indicating the lack of a standardized reference for life cycle studies. In addition, rapid growth in new construction to meet housing demand means that building demolition remains relatively uncommon, limiting empirical evidence on actual building lifespans. Together, these factors confirm that no officially established building service life currently exists in the Cambodian context.

## 5.5.2 Life cycle inventory (LCI)

### 1) The production stage

The material LCI inputs for the production stage were obtained through on-site measurements. After permission for data collection was granted by the house owners, field surveys were conducted using tape measurements, photography, and manual sketching. These activities included measuring all building components, recording the areas of individual rooms, and documenting key structural elements and building façades in detail. The collected sketches and measurements were subsequently translated into two-dimensional drawings of the floor plans, main structural components, and technical details using AutoCAD. A three-dimensional model of

the case study building was then developed in SketchUp to facilitate material quantification and scenario-based modifications.

In cases where material data were incomplete or unavailable for specific building components, reasonable assumptions were made based on in-depth consultations with the building owner, construction engineers, and building equipment suppliers. These consultations were conducted primarily via phone interviews and, where possible, by weighing representative products or materials to determine their mass or quantity for LCI calculations.

The quantities of each material were modeled in the software by dividing materials amount by the GFA of the building. The LCI data for the production phase in the Table 5-2 were modeled by knowing the building materials used in the building elements. The ratio is calculated by amount of building element per m<sup>2</sup> of GFA. The production stage included mainly overall impacts from raw materials acquisition and manufacturing of construction materials at the factory.

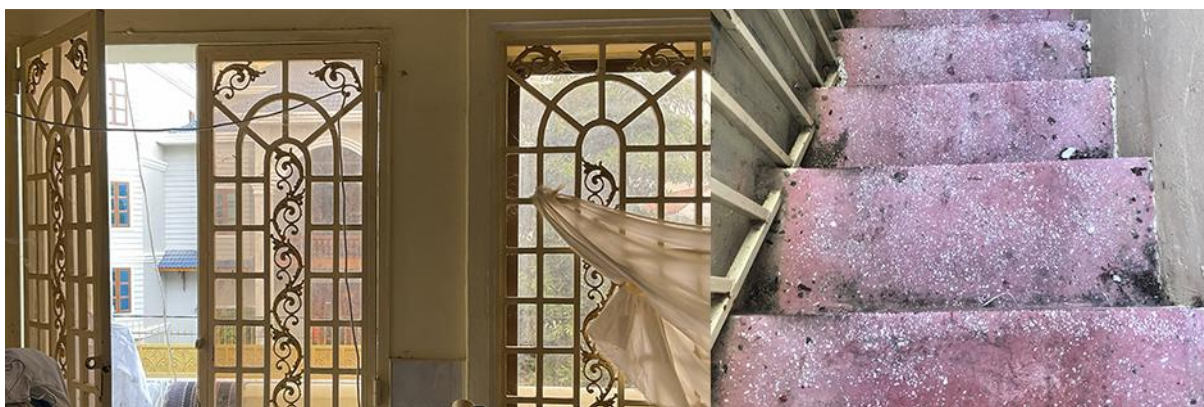
**Table 5-2.** LCI of materials in production phase.

<b>Elements</b>	<b>Materials</b>	<b>Amount</b>	<b>Unit</b>	<b>Ratio</b> [kg/m <sup>2</sup> , m <sup>3</sup> /m <sup>2</sup> , m <sup>2</sup> /m <sup>2</sup> ]
Internal walls	Ceramic tile	1,225.35	kg	7.80
	Clay brick	2,839.2	kg	18.08
	Cement mortar	2,028	kg	12.92
	Base plaster	930	kg	5.92
External walls	Ceramic tile	1,278.83	kg	8.15
	Clay brick	14,196	kg	90.42
	Cement mortar	5,371	kg	34.21
	Base plaster	2,580	kg	16.43
Structures (slab, column, and beam)	Ceramic tile	4,761.40	kg	30.33
	Normal concrete	31.75	m <sup>3</sup>	0.20
	Reinforcing steel	2,715.28	kg	17.29
	Base plaster	1,670	kg	10.64
	Cement mortar	716.22	kg	4.56
Stairs	Steel, low-alloyed	69	kg	0.44
	Alkyd paint	2.5	kg	0.02
	Normal concrete	1.36	m <sup>3</sup>	0.01
	Reinforcing steel	16.74	kg	0.11
Roof shelter	Zinc	300	kg	1.91
	Steel, low-alloyed	412.80	kg	2.63
Doors	Polyvinylchloride	27	kg	0.17
	Wood	4.8	m <sup>2</sup>	0.03
	Alkyd paint	3.2	kg	0.02
	Steel, low-alloyed	92	kg	0.59
	Coated flat glass	30.8	kg	0.20

Windows	Aluminum frame	4.95	m <sup>2</sup>	0.03
	Coated flat glass	84.24	kg	0.54
	Steel, low-alloyed	200.82	kg	1.28
	Alkyd paint	3.6	kg	0.02

The following assumptions were adopted in this study:

- The modeling of all building components includes material production or transformation processes sourced from the ecoinvent database; therefore, transportation to manufacturing facilities was not considered.
- Building services and technical installations were excluded from the production-stage LCI due to restricted access to data related to these systems.
- Owing to the absence of bills of quantities and detailed technical drawings, material quantities estimated from on-site measurements were assumed to be sufficiently accurate for LCI modeling.
- The selection of material types was limited to those available in the ecoinvent 3 database implemented in SimaPro. Consequently, proxy datasets were used where exact matches for the case-study materials were unavailable. For instance, ceramic tiles, one of the dominant materials used in the building, may differ from the database representation in terms of material composition, raw material origin, and manufacturing processes.
- Steel-related building elements, including the external stair to the terrace, stair handrails, structural supports, roof-shelter truss structures, and door and window ornaments (Figure 5-6, left), were modeled as low-alloyed steel, in accordance with available SimaPro recommendations.
- Polished concrete used for the external stair accessing the first floor (Figure 5-6, right) was modeled using a conventional concrete dataset as a proxy.
- All paints applied to the external stair, terrace elements, handrails, doors, and windows were assumed to be alkyd-based paint.



**Figure 5-6.** Steel and paints used for doors and windows' ornaments (left) and polished concrete stair (right).

## **2) The construction stage**

The construction stage accounted exclusively for environmental impacts associated with material losses occurring during on-site construction and installation activities. A uniform material loss rate of 5% was assumed for all building materials, in line with values reported in the literature (Abd Rashid et al., 2015). These losses were modeled by adding an additional 5% of the material inputs from the production stage to represent construction-stage impacts.

## **3) The use stage**

### **a) Use stage - energy**

Electricity is the only form of energy consumed in the studied building, as no energy demand for domestic hot water is required, which was confirmed by the building occupants. Electricity consumption was modeled in the LCA software using the total annual electricity demand (kWh), extrapolated over a 50-year reference study period and normalized per square meter of gross floor area (GFA) for the use stage. The annual electricity demand was estimated based on metered electricity bills covering the most recent twelve-month period up to March 2022.

### **b) Use stage - replacement**

Material replacement during the use phase was modeled based on building components with expected replacement, reapplication, or change over the building life cycle. In this study, painting, windows, and solar PV panels were considered replacement elements. According to Rashid et al. (2017) and Ortiz-Rodríguez et al. (2010), painting and windows were assumed to be replaced four times and once, respectively, over a 50-year service life to maintain building performance (Abd Rashid et al., 2017; Ortiz-Rodríguez et al., 2010). Due to their typical service lifespan, solar PV panels were assumed to be replaced once within the same period.

### **5.5.3 Life cycle impact assessment (LCIA)**

The environmental impacts of the case study are assessed using the EF 3.0 method impact categories, one of the most comprehensive methods for environmental footprint calculation (Mirzaie et al., 2020), considering sixteen impact categories with their indicators as presented in Table 5-3 for the purpose of adequate comparability of results.

**Table 5-3.** Overview of the impact categories considered in the EF 3.0 method (Andreasi Bassi et al., 2023).

<b>Impact category</b>	<b>Acronym</b>	<b>Indicator</b>	<b>Unit</b>
Climate change	GWP	Radiative forcing as Global Warming Potential (GWP100)	kg CO <sub>2</sub> eq
Ozone depletion	OD	Ozone Depletion Potential	kg CFC11 eq
Ionizing radiation	IR	Human exposure efficiency relative to U235	kBq U <sup>235</sup> eq
Photochemical ozone formation	POD	Tropospheric ozone concentration increase	kg NMVOC eq
Particulate matter	PM	Human health effects associated with exposure to PM2.5.	disease inc.
Human toxicity, non-cancer	HT-nc	Comparative Toxic Unit for humans	CTUh
Human toxicity, cancer	HT-c	Comparative Toxic Unit for humans	CTUh
Acidification	AC	Accumulated Exceedance	mol H <sup>+</sup> eq
Eutrophication, freshwater	EUf	Fraction of nutrients reaching freshwater end compartment	kg P eq
Eutrophication, marine	EUm	Fraction of nutrients reaching marine end compartment	kg N eq
Eutrophication, terrestrial	EUt	Accumulated Exceedance	mol N eq
Ecotoxicity, freshwater	ECT	Comparative Toxic Unit for ecosystems	CTUe
Land use	LU	Soil quality index	Pt
Water use	WU	User deprivation potential (deprivation-weighted water consumption)	m <sup>3</sup> depriv.
Resource use, fossils	RD-EF	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ
Resource use, minerals and metals	RD-MM	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq

In this study, the single score represents the overall environmental assessment of the building, calculated in accordance with the EF 3.0 method as recommended by EN 15804+A2 (Mirzaie et al., 2020). The single score was obtained by normalizing and subsequently weighting the results of the sixteen midpoint impact categories, followed by aggregation into a single indicator. Weighting was applied by multiplying the normalized results by their respective weighting factors (Sala et al., 2018).

The single score was calculated using the following equation:

$$\text{Single score} = \sum_{i=1}^n (CV_i \times NF_i \times WF_i) \times 1000$$

where:

- $CV_i$  is the characterized value of impact category  $i$ , expressed in category-specific units (e.g., kg CO<sub>2</sub>-eq for climate change),
- $NF_i$  is the normalization factor for impact category  $i$  (dimensionless),
- $WF_i$  is the weighting factor for impact category  $i$  (percentage),
- $i$  denotes the impact category index, and
- $n$  represents the total number of impact categories considered ( $n = 16$ ).

The multiplication factor of 1000 is applied to scale the results for ease of interpretation, in line with EF 3.0 single-score reporting practice. The normalization and weighting sets used in this study correspond to those published in 2019 for the EF 3.0 method. The values of  $NF_i$  and  $WF_i$  applied in the analysis are presented in Table 5-4.

**Table 5-4.** EF 3.0 normalization and weighting set (SimaPro, 2021).

Impact category	Normalization factor	Weighting factor [%]
Climate change	0.0001235	21.06
Ozone depletion	18.64	6.31
Ionizing radiation	0.000237	5.01
Photochemical ozone formation	0.02463	4.78
Particulate matter	1680	8.96
Human toxicity, non-cancer	4354	1.84
Human toxicity, cancer	59173	2.13
Acidification	0.018	6.20
Eutrophication, freshwater	0.6223	2.80
Eutrophication, marine	0.05116	2.96
Eutrophication, terrestrial	0.005658	3.71
Ecotoxicity, freshwater	0.00002343	1.92
Land use	0.00000122	7.94
Water use	0.00008719	8.51
Resource use, fossils	0.00001538	8.32
Resource use, minerals and metals	15.71	7.55

The ecoinvent 3 databases were chosen for the materials LCIA because these are the most reliable and most used databases for LCA research in the world (Martínez-Rocamora et al., 2016; Wernet et al., 2016). There is not database on materials specific to Cambodia already developed. The utilization of overseas LCI with valid modifications is an effective way to expand its usage and foster the establishment of a localized inventory (Lu et al., 2017) The LCIA concerning electricity consumption are based on the electricity mix in Cambodia. The electricity mix data can be changed and adapted with ecoinvent database according to the local condition and different time as suggested by (Asdrubali et al., 2020; Horváth et al., 2012). The 2021 country electricity mix is dominated by hydropower and coal, at 51.9% and 35.6%, respectively, solar 6.3%, fuel oil 5.7%, and biomass 0.5% (Electricity Authority of Cambodia, 2021).

#### 5.5.4 Interpretation

The results of the life cycle impact assessment were interpreted in accordance with the defined goal and scope of the study and the selected impact categories, including an evaluation of the significance, consistency, and robustness of the results.

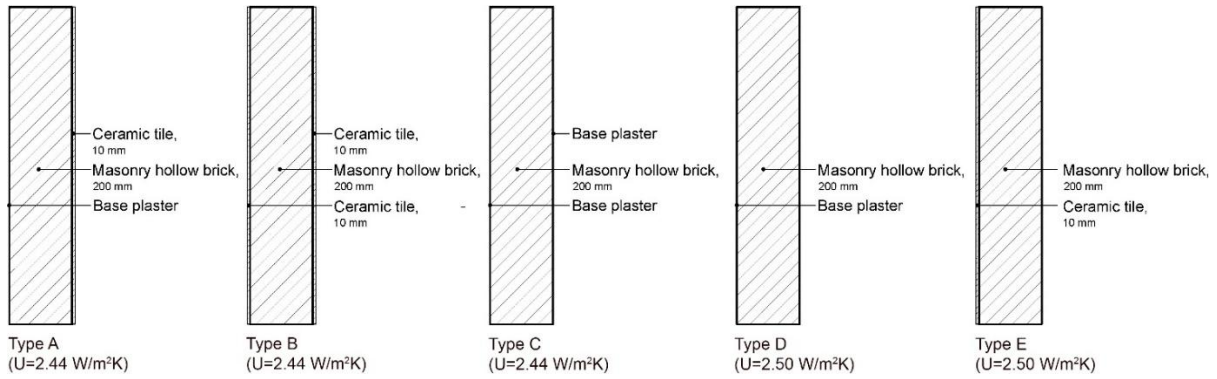
#### 5.5.5 LCA of the scenarios

To study design strategies reducing the carbon footprint and environmental impacts of residential buildings in Cambodia, LCA of several scenarios applied to the case study are carried out and analyzed. The LCA modeling of the scenarios follows the same method and assumptions than the LCA of the existing house, which are described below. In the interpretation, the findings are evaluated by comparing the existing building with the different scenario potentials and their combination.

##### 1) Strategy 1: materials optimization

Strategy 1 is a passive strategy that consists of removing ceramic tile finishes from external wall types A, B, and E (Figure 5-7), as well as eliminating steel frames used as ornamental elements around external windows and doors. The materials proposed for removal in the existing building components are illustrated in Figure 5-8. This strategy aims to minimize the excessive use of ceramic tiles for wall decoration and steel frames for non-structural purposes, compared to typical townhouses in the city where such materials are not commonly applied to these elements.

The external walls were classified into five different types, and their corresponding U-values were calculated as shown in Figure 5-7. The wall typology was defined based on differences in finishing materials and their coverage across various wall surfaces. Based on on-site measurements, all external walls have the same structural thickness; however, base plaster was not applied to wall surfaces shared with adjacent buildings.



**Figure 5-7.** Types of the external walls.



**Figure 5-8.** Ceramic tiles to be removed from the interior of the external wall (left) and steel to be removed from windows and doors (right).

Following the removal of ceramic tile finishes from the external walls, a comparison of the U-values (W/m<sup>2</sup>K) between the existing and modified wall assemblies was conducted. As no dynamic energy simulation was performed for each strategy and annual electricity consumption was assumed to remain constant over the study period, the calculation and comparison of U-values for the existing and modified building components were undertaken to verify their thermal comparability and ensure methodological consistency.

The U-values of the building components are calculated by the following formula and the thermal resistance R-value of materials is shown in the Table 5-5.

$$U_{\text{value}}(\text{building component}) = 1 \div R_T$$

where  $R_T$  (m<sup>2</sup>K/W) is sum of thermal resistance (R-value) of all materials in the building component.

**Table 5-5.** Thermal resistance values of existing and new materials.

Building materials of the walls	Thickness [m]	Thermal conductivity coefficient $\lambda$ [W/m.K]	Thermal resistance R [m <sup>2</sup> K/W]
Base plaster <sup>1</sup>	0.005	0.35	0.01
Cement mortar <sup>1</sup>	0.01	1.15	0.01
Clay brick <sup>1</sup>	0.20	0.52	0.38
Ceramic tile <sup>2</sup>	0.01	1.15	0.01
Reinforced concrete <sup>1</sup>	0.08	1.55	0.05
	0.12	1.55	0.08
Lean concrete <sup>1</sup>	0.08	1.20	0.07
	0.12	1.20	0.10
Timber <sup>1</sup>	0.16	0.17	0.94

<sup>1</sup>National Technical Regulation on Energy Efficiency Buildings, Vietnam: QCVN 09:2017/BXD.

<sup>2</sup>Thermal conductivity value of ceramic tile has been used in the study of (Simões et al., 2000).

The U-value of the existing studied walls and the U-value of the new walls is equal to the same value which is 2.44 W/m<sup>2</sup>K. So, the strategy of removing ceramic tiles on the walls is applicable to the Strategy 1 because the U-values of the existing and new walls are equivalent in terms of thermal comfort for the occupants.

## 2) Strategy 2: use environmental manufacturing process and bio-based materials

Strategy 2 tests the replacement of normal reinforced concrete with lean concrete of density 2250 kg/m<sup>3</sup>. The normal reinforced concrete floors, with U-values of 16.58 W/m<sup>2</sup>K at the ground floor and 9.96 W/m<sup>2</sup>K at the mezzanine, first floor, and terrace, were replaced with lean concrete floors, resulting in reduced U-values of 13.27 W/m<sup>2</sup>K and 8.13 W/m<sup>2</sup>K, respectively. At the ground floor, the concrete flooring was finished with ceramic tiles, while the mezzanine, first floor, and terrace floors were finished with ceramic tiles and a base plaster layer. The reported U-values were calculated by accounting for the thermal properties of the concrete types and the corresponding finishing materials used in each floor assembly.

The U-values of existing normal reinforced concrete and lean concrete are comparable in this case. The environmental impact results from the replacement of normal concrete by lean concrete in this strategy have not been considered in the use stage - energy. Strategy 2 only considered recommendation related to materials, particularly concerning the production stage. The idea of comparing U-value of existing materials and new ones is to see if the new U-value is lower or higher. Thus, if the new U-value is comparable or lower than the existing U-value, the strategy is acceptable and has a potential of thermal comfort improvement. This strategy applies to concrete components such as floor slabs, beams, columns, and stairs.

Moreover, strategy 2 also recommends using bio-based materials; aluminum frames are replaced by wooden window frames. It aims to increase the application of wood material in the building. The wooden frame is a recommended product from the accessible local manufacturing factory,

and a natural product, differently from aluminum which is imported from overseas and consumes more energy and raw materials for the manufacturing process. The existing frames of the external and internal windows and external doors have been replaced.

### **3) Strategy 3: lightweight timber structure**

Strategy 3 investigates natural and local materials to replace the brick masonry walls. It aims to use lightweight timber frames with a thickness of 160 mm for the external walls and preserve the existing structure of concrete frames and internal masonry walls. The composition of the timber walls considered are 10 mm-thickness sheathing boards, timber stud, staples, timber girder, and no thermal insulation materials involved. The U-value of the external wall will be changed from 2.38 W/m<sup>2</sup>K of masonry brick walls to 1.85 W/m<sup>2</sup>K of timber frame walls, which improves the thermal performance of the building.

### **4) Strategy 4: renewable energy utilization**

Strategy 4 aims to implement the solar panels on the existing roof shelter. The type of solar PV panels used is monocrystalline JA Solar JAM60S20-380/MR model with a maximum power output of 380-watt, dimension of 1769 × 1052 × 35 mm, 20.5 kg, made from anti-reflection coating tempered glass, and aluminum alloy frame, and its lifespan of 25 years. A typical crystalline silicon solar panel is made of about, by weight, 76% glass, 10% plastic polymer, 8% aluminum, 5% silicon, 1% copper, and less than 0.1% silver and other metals (Union of Concerned Scientists, 2022). 24 solar panels were installed on the surface of 67 m<sup>2</sup>. In this strategy, the building was at a location with an average 5 peak sun hours per day, and there are 9.12 kW solar panels system with efficiency of 20% (EcoWatch, 2022), thus the simplified calculation of annual solar energy production gives 3,328.8 kWh/year which allows to cover about 51% of the yearly energy consumption. The strategy was modeled by considering the input of total generated solar energy per year and the required electricity to meet either the annual energy consumption in the use phase energy, along with the embodied carbon and embodied energy in solar panels materials in the production phase.

### **5) Combined strategy: the sum of all scenarios**

In the combined strategy, all previously proposed environmental optimization strategies are implemented simultaneously and evaluated as an integrated scenario. This approach aims to assess the cumulative effect of jointly applied strategies on the building case study, with particular emphasis on their impact on carbon emissions and overall environmental impact. The results are compared exclusively between the reference (baseline) scenario and the combined strategy scenario in order to quantify the overall effectiveness of the integrated optimization approach.

## **5.6 RESULTS**

This section presents the LCA results of the studied townhouse in Cambodia. The results include a life cycle impact assessment of all scenarios, comparing their performance across different

environmental impact categories and building life cycle stages, and identifying the most relevant impact categories for the Cambodian building sector (Sub-section 5.6.2). Carbon footprint results for all scenarios are then presented by comparing contributions from individual life cycle stages as well as total life cycle emissions (Sub-section 5.6.3). Sub-sections 5.6.4 and 5.6.5 present the results for the sixteen environmental impact categories, including the characterized results of each scenario, the aggregated environmental footprint (single score), and a comparative analysis across scenarios to identify potential improvements and key trade-offs. Finally, Sub-section 5.6.6 summarizes and compares the carbon and environmental footprint results of the reference scenario and the combined strategy.

### 5.6.1 Life cycle impact assessment of all scenarios

Figure 5-9 illustrates the contribution of each building life cycle stage to the characterized total environmental impacts of the townhouse, comparing the reference scenario with the four proposed strategies across all environmental impact categories. The full table of characterized results for all scenarios, disaggregated by life cycle stage and impact category, is provided in Appendix B. For the purpose of comparison in Figure 5-9, the total impact of each scenario within each impact category was normalized to 100%, and the relative contribution of each life cycle stage was subsequently calculated.

The characterized results across the five scenarios indicate that the use stage dominates most environmental impact categories. For all scenarios, the use stage and the production stage are the most influential life cycle stages across the majority of impact categories, whereas the construction stage contributes only marginally. The production stage is the dominant contributor to specific impact categories, including particulate matter, human toxicity (cancer), and resource use (minerals and metals), accounting for more than 50% of the total impact in each of these categories. An exception is observed in the resource use (minerals and metals) category, where Strategy 4 exhibits a production-stage contribution of less than 50%, in contrast to the other scenarios. In addition, Strategy 3 shows a production-stage contribution exceeding 50% for land use impacts, while the remaining scenarios are dominated by the use stage in this category. Overall, the use stage contributes more than 50% of the total impact in 13 out of the 16 assessed impact categories across all scenarios.

### 5.6.2 The most relevant environmental impact categories

Figure 5-10 presents the normalized and weighted results for the townhouse, using the normalization and weighting factors listed in Table 5-4. The EF 3.0 normalization and weighting set published in November 2019 was applied (SimaPro, 2026). Normalized and weighted results are less commonly reported in LCA studies due to concerns that weighting procedures may downplay well-recognized impacts, such as climate change, relative to other environmental indicators. However, while climate change is a critical impact requiring particular attention, this does not negate the importance of systematically assessing and interpreting other environmental impacts.

Based on the EF 3.0 method, the most relevant environmental impact categories for the studied building are illustrated in Figure 5-10. Climate change emerges as the most significant impact category, driven by both high operational energy consumption and the relatively high weighting factor assigned to the GWP indicator. The weighting factor for climate change (21.06%) is more than twice that of the second-highest weighted indicator, as shown in Table 5-4.

In terms of hotspot analysis (i.e., identifying the most relevant environmental indicators) and benchmarking (i.e., communicated separately as 'other impact results'), the PEFCR guidance document states that three indicators: ecotoxicity freshwater (aquatic), human toxicity - cancer, and human toxicity - non-cancer should be excluded from these analyses but still included in the characterized results (EC, 2017). Excluding toxicity-related indicators, such as freshwater ecotoxicity, from the set of mandatory categories for hotspot identification following recommendations from the literature (Mirzaie et al., 2020; Saouter E et al., 2020), the five most relevant impact categories for the case study are identified as:

- Climate change
- Particulate matter
- Resource use (fossils)
- Acidification
- Water use

Among these, particulate matter represents the second most critical impact category. On average across all scenarios, climate change and particulate matter together account for approximately 44% of the total weighted environmental impacts. Given the dominant influence of the use stage observed in the results, Figure 5-10 further highlights this stage as the primary contributor to the most significant weighted impacts. In addition, resource use (minerals and metals) and photochemical ozone formation impacts are identified as key indicators when evaluating operational and embodied environmental impacts, respectively.

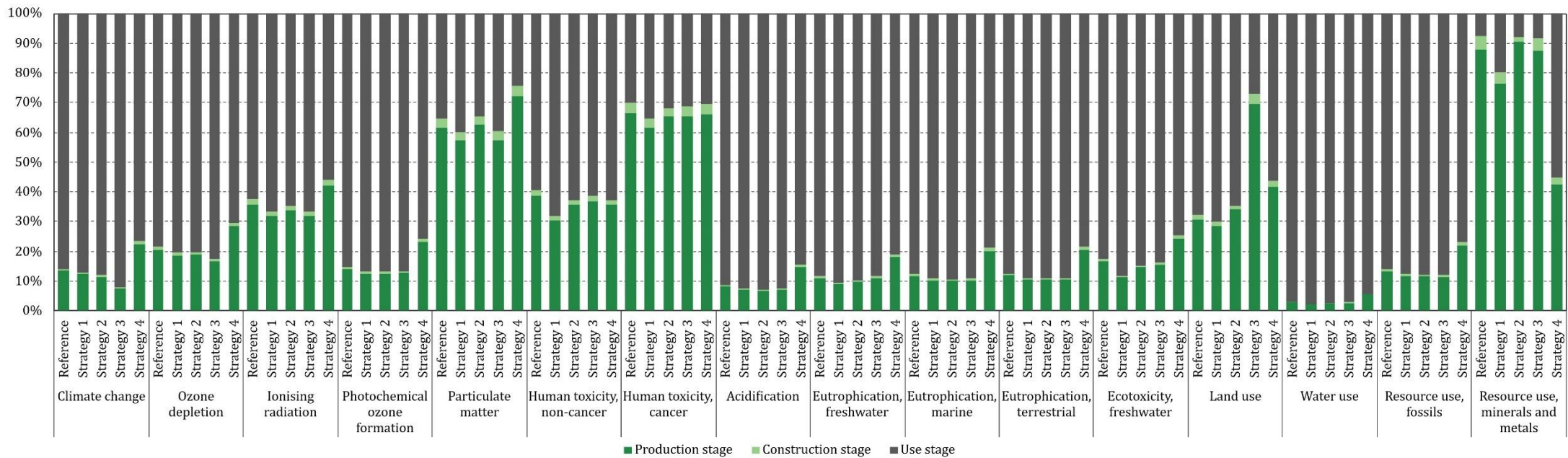


Figure 5-9. characterized life cycle impacts of the townhouse as per different scenarios.

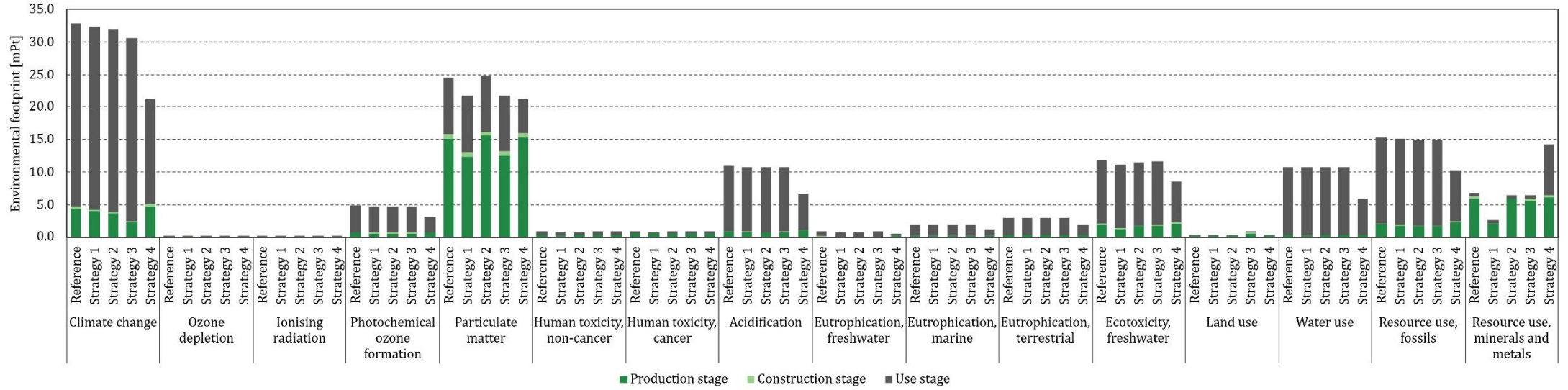
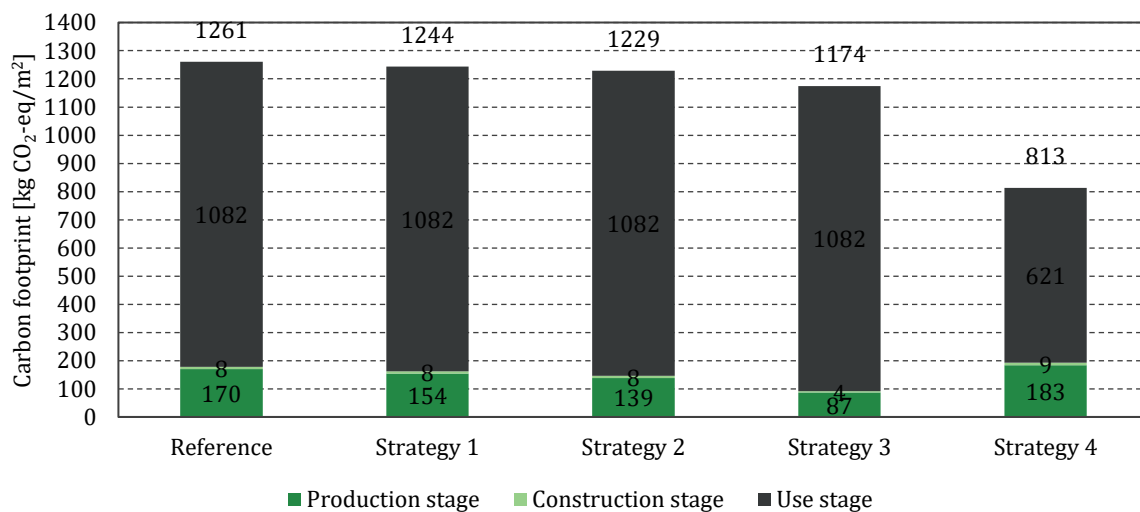


Figure 5-10. The normalized and weighted life cycle impacts of the townhouse as per different scenarios.

### 5.6.3 Carbon footprint of the townhouse and different scenarios

As life cycle carbon emission assessment is a key objective of this study aiming to quantify the carbon footprint of a townhouse as a representative residential building in the Cambodian construction sector, and given that climate change has been identified as the most critical environmental hotspot, this section analyzes and compares the carbon footprint results of all scenarios across the different building life cycle stages. Figure 5-11 compares the climate change impacts, expressed as carbon footprint using the Global Warming Potential over 100 years (GWP100) of the reference scenario and the four investigated strategies across the selected life cycle stages of the townhouse case study. The reference scenario, representing the existing condition of the building, is dominated by the use stage, which contributes the highest share to the total carbon footprint. Specifically, the use stage accounts for 1060 kg CO<sub>2</sub>-eq/m<sup>2</sup>, corresponding to approximately 84% of the total GWP. This high contribution is primarily attributed to the building's electricity consumption during operation.

The production stage represents the second-largest contributor, with a carbon footprint of 170 kg CO<sub>2</sub>-eq/m<sup>2</sup>, accounting for approximately 13% of the total life cycle emissions. This impact is mainly associated with the manufacturing processes and production of building materials. The construction stage exhibits the smallest contribution, at 8 kg CO<sub>2</sub>-eq/m<sup>2</sup>, consistent with finding (Cho & Chae, 2016; Morsi et al., 2020; Abd Rashid et al., 2017; You et al., 2011).



**Figure 5-11.** Carbon footprint (GWP100) of the existing townhouse and the four assessed scenarios across life cycle stages.

As shown in Figure 5-11, Strategy 1, which focuses on eliminating unnecessary material use and excessive finishing layers, achieves a modest 1% reduction in the overall carbon footprint compared to the reference scenario. Although the reduction is limited, this strategy represents a best-practice approach that can be readily implemented where applicable and contributes incrementally to impact mitigation.

Strategy 2 results in a 3% decrease in total carbon footprint through the substitution of conventional materials with alternatives produced via lower-carbon processes, specifically lean concrete and timber window frames. Together, Strategies 1 and 2 demonstrate a positive, albeit moderate, reduction in climate change impact from a building materials perspective, indicating that material efficiency and low-carbon material substitution alone led to limited but measurable improvements in overall life cycle performance.

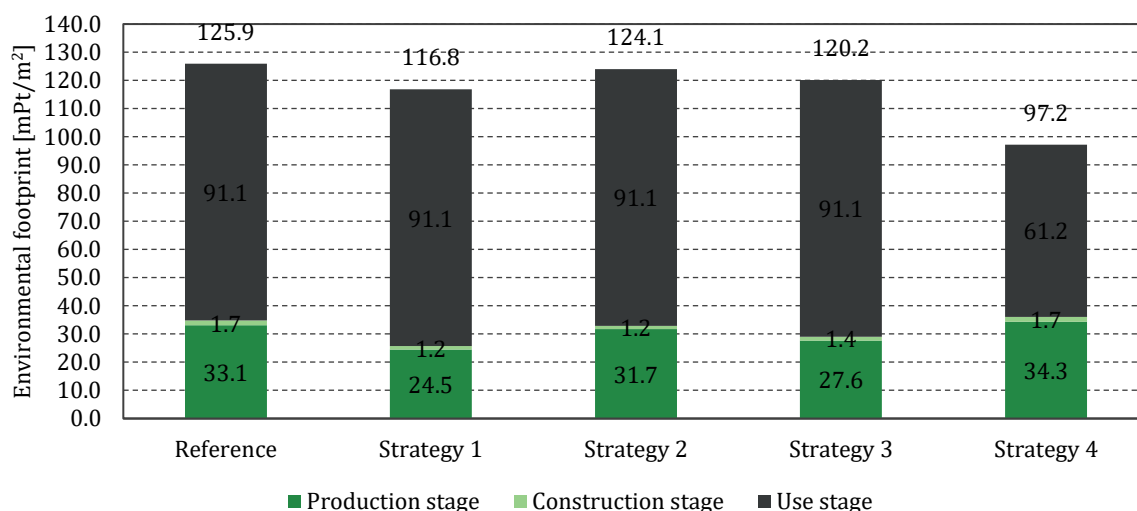
A more pronounced reduction is observed for Strategy 3, which achieves a 7% decrease in carbon footprint relative to the reference scenario (Figure 5-11). This outcome supports the adoption of natural and low-impact materials, particularly lightweight timber frame wall systems, as recommended by building professionals and previous research, while also aligning with the local construction context and vernacular architecture. Strategy 3 is considered acceptable in terms of environmental performance, building functionality, and local availability. Moreover, the use of lightweight timber enables local manufacturing and supply, resulting in reduced transportation and construction costs and lower production-stage emissions, which is especially relevant in the Cambodian context. Compared to Strategies 1 and 2, Strategy 3 exhibits a greater reduction in emissions at the production and construction stages, as well as across the overall life cycle. Consequently, Strategies 1, 2, and 3 each targeting building material optimization and mutually compatible in application, are identified as effective material-based mitigation strategies for the case study.

The most substantial reduction is achieved by Strategy 4, which realizes a 35% decrease in carbon footprint compared to the reference scenario, as illustrated in Figure 5-11. This significant improvement is primarily attributed to the installation of rooftop solar PV panels, which markedly reduce electricity consumption during the use stage. Accordingly, solar energy integration emerges as the most effective strategy among those evaluated from a carbon reduction perspective. However, Strategy 4 also results in an approximately 8% increase in production stage emissions relative to the reference scenario, due to the embodied emissions associated with the manufacture of PV panels and their constituent materials. The additional material demand for PV modules and their structural integration with the roof shelter contributes to this increase. In particular, glass and aluminum, materials characterized by energy-intensive manufacturing processes and limited recyclability are major contributors to the higher production stage emissions.

#### 5.6.4 Environmental footprint of the existing house and different scenarios

Figure 5-12 presents a comparison of the single-score environmental footprints of all scenarios, disaggregated by life cycle stage. The corresponding characterized, normalized, and weighted values are provided in Appendix B. The reference scenario exhibits a total environmental footprint of 125.9 mPt/m<sup>2</sup>, with two stages dominating the overall impact: the use stage, contributing 91.1 mPt/m<sup>2</sup>, and the production stage, contributing 33.1 mPt/m<sup>2</sup>. These stages account for approximately 72% and 26% of the total single score, respectively, indicating that the use stage–energy is the primary contributor to the environmental footprint. Notably, the single

score of the production stage corresponds to approximately 36% of that of the use stage, confirming the dominant role of operational energy use in the overall environmental impact. In contrast, the construction stage exhibits minor contribution.



**Figure 5-12.** Comparison of single-score environmental footprints of the reference scenario and the four strategies by life cycle stage.

Relative to the reference scenario, Strategies 1, 2, 3, and 4 achieve reductions in the overall single-score environmental footprint of approximately 7%, 1%, 5%, and 23%, respectively (Figure 5-12). Among these, Strategy 4 yields the largest overall reduction, driven primarily by improvements in the use stage–energy. However, Strategy 1 is the most effective in reducing production-stage impacts, achieving an approximately 26% decrease compared to the production stage of the reference scenario. This reduction is attributed to the elimination of excessive and unnecessary building materials.

Strategy 2 demonstrates the least improvement in minimizing production-stage environmental impacts when compared to the other material-optimization strategies (Strategies 1 and 3). Strategy 3 exhibits intermediate environmental performance between Strategies 1 and 2, both at the production stage and in terms of the overall footprint. The introduction of lightweight timber frame walls in Strategy 3 contributes positively to reducing the environmental impacts associated with building materials.

In Strategy 4, the installation of rooftop solar PV panels significantly reduces household electricity demand from the grid, resulting in an approximate 35% reduction in the use stage–energy environmental impact relative to the reference scenario. Nevertheless, this strategy also leads to an increase of approximately 4% in the production-stage environmental footprint, due to the embodied impacts associated with the manufacture of PV panels. While Strategy 4 is therefore less effective in minimizing production-stage impacts, it delivers substantial benefits at the use stage–energy and achieves the greatest reduction in the overall environmental footprint.

Overall, the results indicate that achieving meaningful reductions in environmental impacts across all life cycle stages requires the combination of multiple strategies. For the studied building, integrating Strategy 4, which targets the use stage–energy, with Strategy 1 and/or Strategy 3, which address material-related impacts, offers the most effective approach to minimizing the total environmental footprint across the building life cycle.

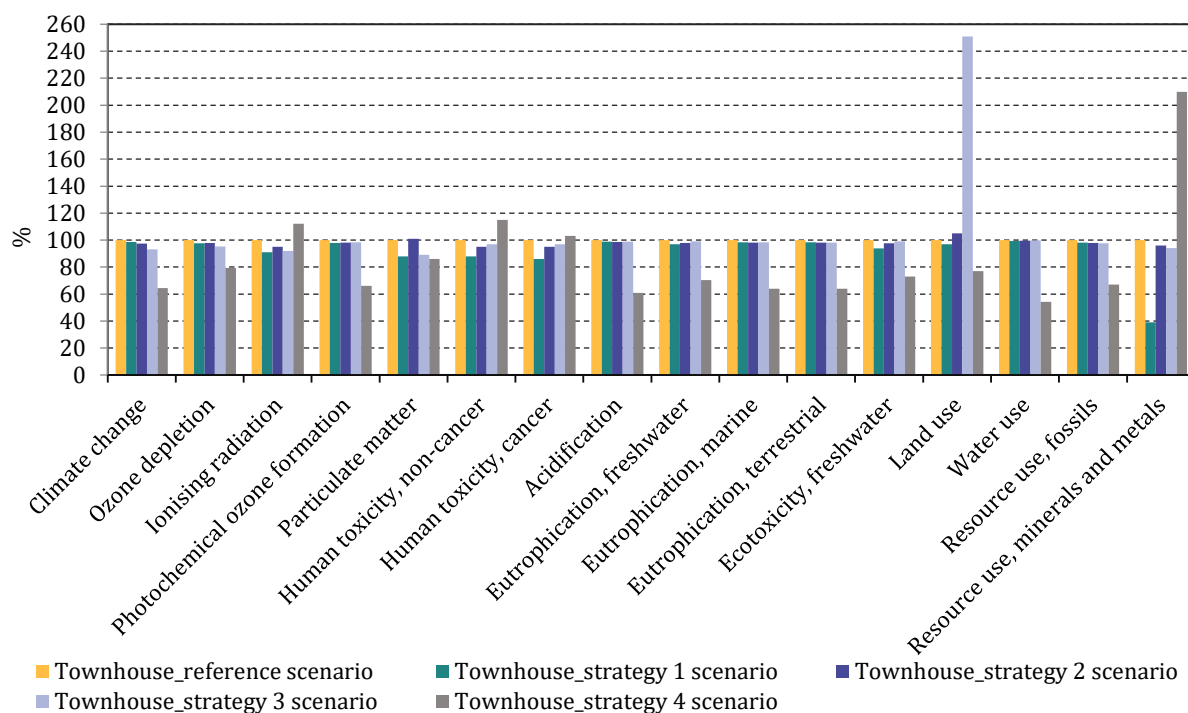
#### **5.6.5 LCA results of all scenarios in sixteen environmental impacts**

Table 5-6 presents the characterized results for each scenario across all environmental impact categories. These values represent the aggregated impacts from all considered life-cycle stages and serve as the basis for determining the single-score environmental footprint results (in millipoints) for each scenario, as illustrated in the previous section. Detailed characterized, normalized, and weighted results for all scenarios and impact categories are provided in Appendix B. The drivers and influences underlying the changes observed in key impact categories are further analyzed with reference to Figure 5-13.

**Table 5-6.** Accumulated results over the building's life cycle by impact category of each scenario.

<b>Impact category [Unit/m<sup>2</sup>]</b>	<b>Reference</b>	<b>Strategy 1</b>	<b>Strategy 2</b>	<b>Strategy 3</b>	<b>Strategy 4</b>
Climate change [kg CO <sub>2</sub> eq]	1.26E+03	1.24E+03	1.23E+03	1.17E+03	8.13E+02
Ozone depletion [kg CFC11 eq]	4.79E-05	4.68E-05	4.69E-05	4.57E-05	3.80E-05
Ionizing radiation [kBq U-235 eq]	1.68E+01	1.58E+01	1.63E+01	1.58E+01	1.54E+01
Photochemical ozone formation [kg NMVOC eq]	4.09E+00	4.00E+00	4.01E+00	4.02E+00	2.70E+00
Particulate matter [disease inc.]	1.63E-04	1.44E-04	1.65E-04	1.45E-04	1.41E-04
Human toxicity, non-cancer [CTUh]	1.04E-05	9.08E-06	9.84E-06	1.01E-05	1.19E-05
Human toxicity, cancer [CTUh]	6.63E-07	5.67E-07	6.29E-07	6.40E-07	6.83E-07
Acidification [mol H <sup>+</sup> eq]	9.78E+00	9.66E+00	9.63E+00	9.67E+00	5.96E+00
Eutrophication, freshwater [kg P eq]	4.60E-02	4.49E-02	4.52E-02	4.59E-02	3.10E-02
Eutrophication, marine [kg N eq]	1.29E+00	1.27E+00	1.27E+00	1.27E+00	8.27E-01
Eutrophication, terrestrial [mol N eq]	1.45E+01	1.42E+01	1.42E+01	1.42E+01	9.25E+00
Ecotoxicity, freshwater [CTUe]	2.62E+04	2.46E+04	2.56E+04	2.59E+04	1.91E+04
Land use [Pt]	3.56E+03	3.45E+03	3.74E+03	8.92E+03	2.73E+03
Water use [m3 depriv.]	1.46E+03	1.46E+03	1.46E+03	1.46E+03	7.93E+02
Resource use, fossils [MJ]	1.20E+04	1.18E+04	1.17E+04	1.17E+04	8.04E+03
Resource use, minerals and metals [kg Sb eq]	5.72E-03	2.24E-03	5.50E-03	5.37E-03	1.20E-02

Figure 5-13 illustrates the comparative performance of the reference scenario and the four studied strategies across 16 environmental impact categories. Overall, each strategy achieves reductions in several impact categories relative to the reference scenario, with improvements observed in 10 out of the 16 categories across the evaluated strategies. However, the results also reveal trade-offs, as certain strategies increase specific environmental impacts.



**Figure 5-13.** Comparison of 16 environmental impact categories for the reference scenario and the four evaluated strategies.

Strategy 1 demonstrates notable reductions in several material-related impact categories, including a 61% decrease in resource use, minerals and metals, a 14% reduction in human toxicity (cancer), and reductions of approximately 12% in both particulate matter and human toxicity (non-cancer) compared to the reference scenario. Importantly, Strategy 1 does not increase any environmental impact category, indicating that minimizing excessive material use and finishes is an effective and robust mitigation approach with no adverse environmental trade-offs.

In contrast, Strategy 2, which focuses on substituting conventional materials with lower-carbon alternatives, shows limited improvements across the full range of impact categories over the building life cycle. Moreover, this strategy results in a 5% increase in land use impact compared to the reference scenario, suggesting that material substitution alone may shift environmental burdens rather than consistently reduce them across all categories.

Strategy 3 reduces particulate matter impacts by approximately 11%, confirming the benefits of using natural and lightweight materials. However, it also leads to a substantial 151% increase in land use impact relative to the reference scenario. While the use of timber-based materials is advantageous for mitigating several environmental impacts, the production of timber can involve

deforestation and significant land occupation. These findings highlight that the implementation of natural materials should be closely linked to sustainable forest management and land-use planning to avoid unintended environmental consequences.

Strategy 4 achieves reductions in 12 of the 16 impact categories, representing the broadest improvement among the evaluated strategies. Nevertheless, it also causes pronounced increases in specific impacts, including 110% for resource use, minerals and metals, 15% for human toxicity (non-cancer), 12% for ionizing radiation, and 3% for human toxicity (cancer). These increases are primarily associated with the production of photovoltaic (PV) panels, which involves energy-intensive manufacturing processes, high water consumption, the use of toxic chemicals, and the generation of manufacturing waste (Energy5, 2023). The observed trade-offs underscore the importance of accounting for raw material demand, human toxicity, and ionizing radiation when evaluating PV-based mitigation strategies. Furthermore, as emerging PV technologies increasingly rely on materials with potential toxic effects, their environmental impacts should be explicitly addressed and minimized during the technology design and development phase (Cellura et al., 2024).

### 5.6.6 Results comparison of the reference and combined strategy

Table 5-7 summarizes the carbon footprint, expressed as GWP in kg CO<sub>2</sub>-eq/m<sup>2</sup>, and the overall environmental footprint, expressed as a single score in mPt/m<sup>2</sup> derived from all 16 assessed environmental impact categories, for both the reference scenario and the combined strategy across the different life cycle stages of the building.

**Table 5-7.** Carbon footprint (GWP) and aggregated environmental footprint by life cycle stage for the reference scenario and the combined strategy.

Life cycle stage	Reference		Combined strategy	
	Carbon footprint [kg CO <sub>2</sub> -eq/m <sup>2</sup> ]	Environmental footprint [mPt/m <sup>2</sup> ]	Carbon footprint [kg CO <sub>2</sub> -eq/m <sup>2</sup> ]	Environmental footprint [mPt/m <sup>2</sup> ]
Total	1.26E+03	125.9	6.67E+02	87.7
Production	1.70E+02	33.1	6.58E+01	27.1
Construction	8.50E+00	1.7	3.29E+00	1.4
Use	1.08E+03	91.1	5.98E+02	59.2

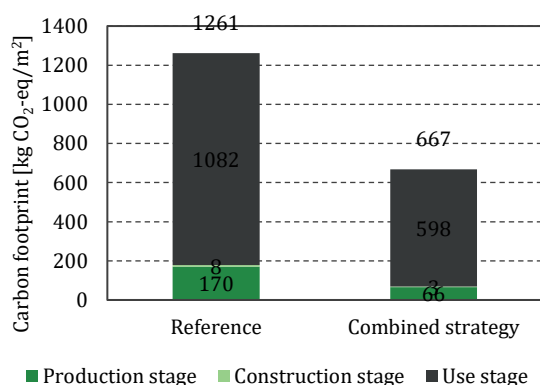
Figure 5-14 and Figure 5-15 present the carbon footprint and environmental footprint results for the reference scenario and the combined strategy across the different stages of the building life cycle. Detailed characterized, normalized, and weighted results supporting these figures are provided in Appendix B. The combined application of the four studied strategies results in substantial reductions in both indicators at all life cycle stages. Under the combined strategy, the total carbon footprint is reduced to 667 kg CO<sub>2</sub>-eq/m<sup>2</sup>, while the total environmental footprint decreases to 87.7 mPt/m<sup>2</sup>.

Overall, the combined strategy achieves a 47% reduction in carbon footprint and a 30% reduction in environmental footprint compared to the reference scenario. Despite these improvements, the use stage-energy remains the dominant contributor to the total carbon footprint, accounting for approximately 88% of the life cycle impacts.

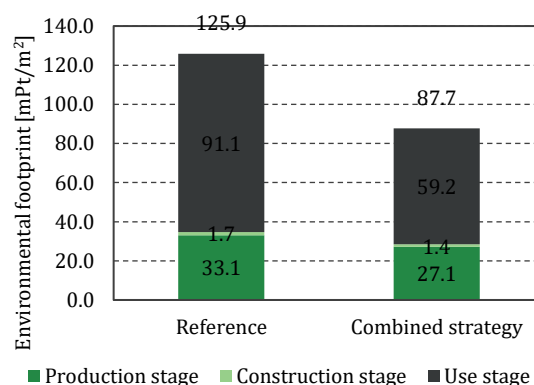
A stage-by-stage comparison of carbon footprint shows that the combined strategy results in reductions of 61% in the production stage, 61% in the construction stage, 45% in the use stage relative to the corresponding stages of the reference scenario. These results indicate substantial mitigation potential for greenhouse gas emissions at multiple stages of the building life cycle.

When isolating the contribution of individual strategy groups, the material-focused strategies (Strategies 1, 2, and 3) collectively achieve a reduction of 104 kg CO<sub>2</sub>-eq/m<sup>2</sup> (61%) in the production stage compared to the reference scenario. In contrast, Strategy 4, which targets operational energy demand, leads to a reduction of 484 kg CO<sub>2</sub>-eq/m<sup>2</sup> (including also impact from use stage - replacement) in the use stage. These findings highlight that material-based decarbonization strategies are particularly effective in reducing production stage emissions, while energy-related strategies primarily drive reductions during the use stage. Consequently, the dominant contributors to the overall carbon footprint reduction in the combined strategy remain the use stage (dominating by use stage - energy), followed by the production stage.

With respect to the aggregated environmental footprint, the combined strategy achieves reductions of 18% in both the production and construction stages and 35% in the use stage compared to the reference scenario. The resulting decrease in the total single score environmental footprint representing the combined effects of all sixteen assessed impact categories, demonstrates that the integrated application of the four strategies provides a notable improvement in environmental performance across all evaluated life cycle stages for the townhouse case study.



**Figure 5-14.** Comparison of carbon footprint (GWP) results for the reference scenario and the combined strategy across life cycle stages.



**Figure 5-15.** Comparison of single-score environmental footprint results for the reference scenario and the combined strategy across life cycle stages.

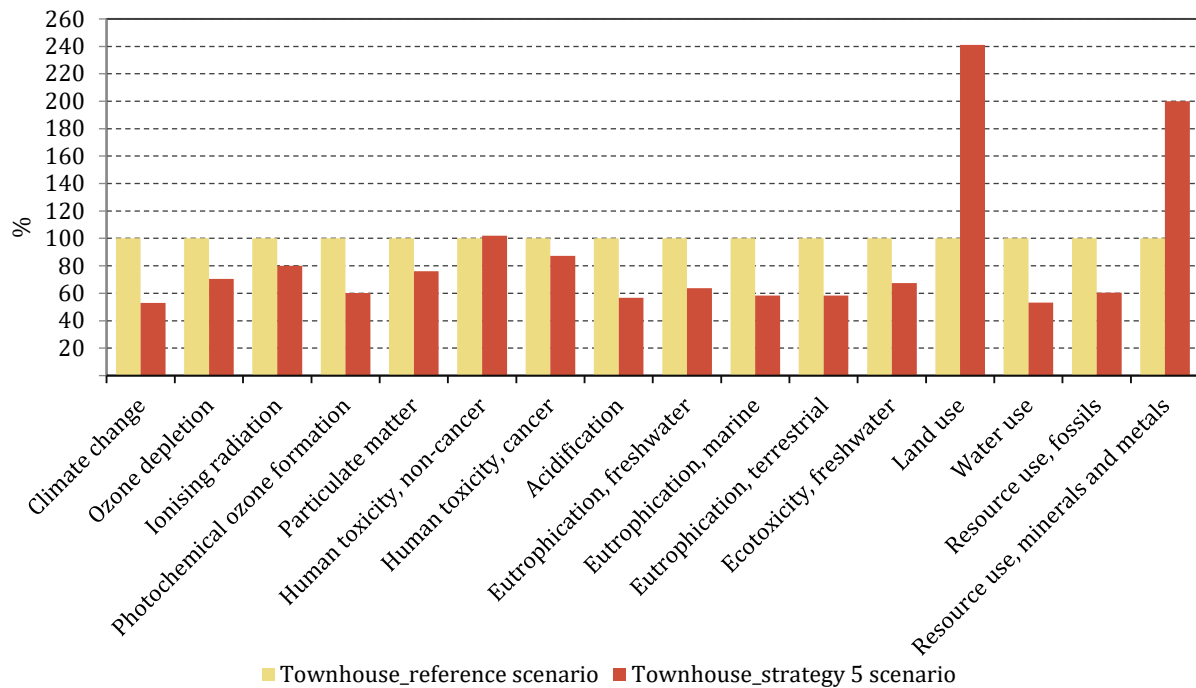
Figure 5-16 compares the sixteen assessed environmental impact categories for the reference scenario and the combined strategy. The combined application of the four strategies

demonstrates a strong potential to reduce environmental impacts across nearly all categories. Specifically, reductions of approximately 47% are observed for both climate change and water use, while acidification decreases by 43%, and eutrophication (marine) and eutrophication (terrestrial) are reduced by 42% relative to the reference scenario.

In contrast, certain impact categories increase under the combined strategy. Land use exhibits a substantial increase of approximately 141%, while resource use, minerals and metals rises by 100%, and human toxicity (non-cancer) increases slightly by 2% compared to the reference scenario. These increases are primarily attributable to Strategy 3, involving the implementation of lightweight timber frame walls, and Strategy 4, which includes the installation of photovoltaic (PV) panels, as previously illustrated in Figure 5-13.

The observed increases highlight important trade-offs associated with the use of biogenic materials and PV technologies and underscore the need for targeted mitigation measures during building design and material sourcing. In particular, the elevated land use impact linked to timber production emphasizes the importance of sustainable forestry practices. In the Cambodian context, this can be addressed by prioritizing timber sourced from sustainably managed forests certified under internationally recognized schemes such as the Forest Stewardship Council (FSC) or the Programme for the Endorsement of Forest Certification (PEFC), as well as by strengthening national forest governance and promoting plantation-based timber production. Similarly, the increased demand for minerals and metals associated with PV systems could be mitigated through the selection of high-efficiency panels with longer service lives, recycling of critical materials, and the development of regional supply chains to reduce upstream impacts.

Despite these trade-offs, from a climate change perspective, the use of biogenic materials offers clear environmental benefits. Trees absorb carbon dioxide during growth and store biogenic carbon, allowing timber-based construction systems to achieve significantly lower life-cycle greenhouse gas emissions than conventional masonry or concrete alternatives. When combined with responsible forest management and sustainable material sourcing, timber-based solutions can therefore contribute to climate-efficient and environmentally balanced building design in Cambodia.



**Figure 5-16.** Comparison of sixteen environmental impact categories for the reference scenario and the combined strategy.

### 5.6.7 Discussion on building LCA in Cambodia and comparison with similar studies

To validate the robustness of the results, this study compares the carbon footprint outcomes of the reference scenario and the combined strategy with findings from the existing literature. The LCA results of carbon footprint of the townhouse case study in Cambodia is benchmarked against reported values for buildings from different contexts, taking into account life cycle stages considered in each assessment.

In Belgium, Opdebeeck et al. (2016) found that a passive terraced house, needing 15 kWh/(m<sup>2</sup>.year) of heating or cooling consumption, with a lifespan of 50 years emits between 415 and 765 kg CO<sub>2</sub>-eq/m<sup>2</sup> while a low energy house, consuming 38 kWh/(m<sup>2</sup>.year), emits between 895 and 1245 kg CO<sub>2</sub>-eq/m<sup>2</sup>, depending on materials chosen (Opdebeeck et al., 2016). However, they did not consider household’s electricity consumption related to ventilation and electrical appliances. Considering all heating and electric consumption, Nematchoua et al. (2022) found an overall carbon footprint of 1790 kg CO<sub>2</sub>-eq/m<sup>2</sup> for a low energy multi-family residential building in Belgium (Nematchoua et al., 2022). In Thailand, a comparative LCA study of a detached typical, nearly net zero energy, and net zero energy house gives a carbon footprint on its whole life cycle of 3525 kg CO<sub>2</sub>-eq/m<sup>2</sup>, 1232.4 kg CO<sub>2</sub>-eq/m<sup>2</sup>, and 658.7 kg CO<sub>2</sub>-eq/m<sup>2</sup> respectively (Iqbal et al., 2018). By analyzing 238 building LCA studies in Europe, Röck et al. (2020) found that the average share of embodied carbon emissions from buildings following current energy performance regulations is approximately 20 – 25% of the overall carbon footprint, while the embodied carbon emissions of positive energy buildings using on site renewable energy sources can reach the level of 45% of their overall life cycle carbon footprint or even more (Röck, Balouktsi, et al., 2020).

Based on these studies, we can consider that the orders of magnitude of our results are equivalent to other studies published in the literature, which validates our results. Comparing the orders of magnitude of a LCA study with other similar studies is useful in the context of this validation. However, it should be noted that the results of different LCAs are never perfectly comparable because the studies will most likely differ in terms of basic data, system boundaries, inventory modeling, functional unit, etc.

Based on selected building LCA studies conducted in comparable contexts namely region (Southeast Asia), economic level (developing countries), and climate (tropical climates), the carbon footprints of the reference and combined strategy scenarios in this study were compared across different building typologies and life-cycle stages using a consistent indicator, namely carbon emissions.

The comparison included both the reference townhouse and the low-environmental impact townhouse resulted from combined strategy in Cambodia (this study), two scenarios of design alternatives of a green office building in Vietnam (Le et al., 2021), a single-family house in Indonesia (Satola et al., 2021), a one-floor detached house type 1A, a two-floor detached house type 2A, and a two-floor detached house type 2C in Thailand (Viriyaroj et al., 2024), a semi-detached house in Malaysia (Abd Rashid et al., 2017), a six-storey rammed up food factory in Singapore (Kua et al., 2012), Luzon single-family dwellings in the Philippines (Arceo et al., 2023), and a three-storey residential building in Myanmar (Myint et al., 2024), as presented in Table 5-8. As Cambodia represents a low-income, developing tropical country in Southeast Asia, this section also aims to include a broader and more inclusive comparison of building LCA studies from neighboring countries with similar socio-economic conditions to enhance the regional representativeness of the results. However, no relevant studies from Lao PDR, also a low-income country, were available for inclusion in this comparative analysis.

Due to the lack of consistent reporting across the reviewed studies, detailed results for all building life cycle stages were not always available. In several cases, carbon emissions from the production and construction stages were reported as a combined value. Consequently, the comparison of carbon footprint proportions across studies is structured around three aggregated stages: production and construction, use stage, and total life cycle. Exceptions include the case studies from the Philippines, which considered only the A1-A3 life cycle modules (i.e., the production stage), and Myanmar, for which comparisons could be made only for the production and construction stages due to the absence of use-stage results.

**Table 5-8.** Comparison table of carbon footprint proportions in each life cycle stage across buildings LCA case studies in Southeast Asia countries.

Reference	Case study	Typology (Residential, office, etc.)	Country	Southeast Asia/Developing country/Tropical climate	GFA or TFA [m <sup>2</sup> ]	Carbon footprint [kg CO <sub>2</sub> -eq/m <sup>2</sup> ]		
						Production and construction stage	Use stage	Total
This study	Townhouse	Residential	Cambodia	SEA/DEV/TRP	157	178	1,082	1,261
This study	Low-environmental impact townhouse	Residential	Cambodia	SEA/DEV/TRP	157	69	598	667
Le et al., 2021	Green building: 1st scenario	Office	Vietnam	SEA/DEV/TRP	14,112	474	861	1,335
Le et al., 2021	Green building: 2nd scenario	Office	Vietnam	SEA/DEV/TRP	14,112	475	359	834
Satola et al., 2021	Single-family house type CS47ID	Residential	Indonesia	SEA/DEV/TRP	207	135	1,363	1,498
Viriyaraj et al., 2024	1-floor detached house type 1A	Residential	Thailand	SEA/TRP	75.91	627	3,183	3,810
Viriyaraj et al., 2024	2-floor detached house type 2A	Residential	Thailand	SEA/TRP	159.34	408	1,887	2,294
Viriyaraj et al., 2024	2-floor detached house type 2C	Residential	Thailand	SEA/TRP	264.45	357	1,742	2,099
Abd Rashid et al. 2017	Semi-detached house	Residential	Malaysia	SEA/TRP	246	828	2,502	3,330
Kua et al., 2012	6-storey rammed up food-factory	Commercial	Singapore	SEA/TRP	52,094	201	1,165	1,367
Arceo et al., 2023	Luzon single-family dwellings	Residential	Philippines	SEA/DEV/TRP	-	313	-	313
Myint et al., 2024	3-storey residential building	Residential	Myanmar	SEA/DEV/TRP	456	520	-	520

SEA: Southeast Asia, DEV: Developing country, TRP: Tropical climate, GFA: gross floor area, and TFA: total floor area.

Differences in carbon footprint results across life cycle stages among the reviewed studies are partly attributable to variations in study objectives and system boundaries. For example, some studies include replacement and operational energy within the use stage (this study), while others account for maintenance and electricity use (Le et al., 2021), replacement together with energy and water use (Viriyaraj et al., 2024), maintenance and energy use (Abd Rashid et al., 2017), operational energy and renovation (Kua et al., 2012), or overall operational impacts (Satola et al., 2021). In addition, particular attention should be given to the Indonesian case, where results are reported as life cycle embodied carbon. This approach may include emissions not only from the production and construction stages but also from other material-related stages, which limits direct comparability with studies applying different system boundaries.

Figure 5-17 compares the carbon footprint and life-cycle stage contributions of the studied townhouse with results from other building LCA studies in Southeast Asia. The total carbon footprint in this study ranges from 1,261 kg CO<sub>2</sub>-eq/m<sup>2</sup> for the reference scenario to 667 kg CO<sub>2</sub>-eq/m<sup>2</sup> for the low-environmental-impact townhouse. By comparison, reported values for other buildings in Vietnam, Singapore, Indonesia, Thailand (house types 2A and 2C), Malaysia, and Thailand (house type 1A) are generally higher, at 1,335, 1,367, 1,498, 2,099, 2,294, 3,330, and 3,810 kg CO<sub>2</sub>-eq/m<sup>2</sup>, respectively. Overall, the case study townhouse in Cambodia is comparable to cases in Vietnam, Singapore, and Indonesia, where total carbon footprints typically fall within the range of 1,250–1,500 kg CO<sub>2</sub>-eq/m<sup>2</sup>.

Across all seven countries, the use stage is the dominant contributor to life-cycle carbon emissions. Operational energy demand plays a critical role in determining overall performance, particularly for buildings with high cooling and electricity consumption. Nevertheless, the magnitude of this contribution depends on national energy mixes, building efficiency, and whether the buildings are newly constructed or retrofitted. For example, in Colombia the Pamplona house exhibits a lower proportional impact from the use stage compared with the Barcelona house in Spain (Ortiz-Rodríguez et al., 2010). Similarly, in Vietnam, a second design alternative incorporating improved materials, efficient air-conditioning and lighting systems, and water-saving sanitary equipment resulted in a reduced use-stage impact relative to the combined production and construction stage.

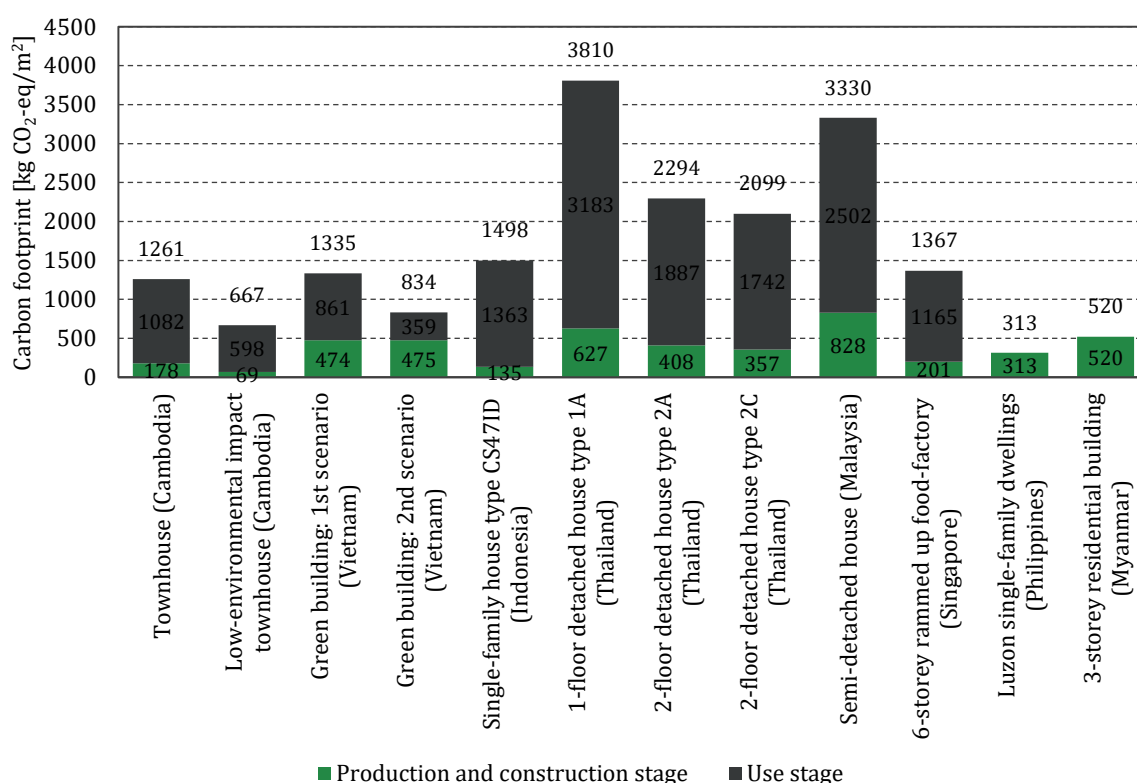
In many of the reviewed studies, higher operational carbon emissions are associated with elevated energy consumption supplied by electricity, gas, fuel, and coal. This leads to substantially higher life-cycle emissions compared with the present study. The higher household energy demands reported by Satola et al. (2021), Viriyaraj et al. (2024), and Abd Rashid et al. (2017) reflect strong variations in per-capita energy use among countries (Abd Rashid et al., 2017; Satola et al., 2021; Viriyaraj et al., 2024). As shown in Figure 5-17, operational energy contributes approximately 85% of the total footprint for the reference townhouse in Cambodia, while corresponding shares are about 91% in Indonesia, 82–84% in Thailand, and 75% in Malaysia.

According to the International Energy Agency (IEA), energy demand per capita in Southeast Asia correlates strongly with GDP per capita (IEA, 2022). Cambodia's per-capita energy consumption

in 2019 was among the lowest in the region, about half the Southeast Asian average, which itself remains below the global average, whereas Thailand, Malaysia, Singapore, and Brunei Darussalam exhibit energy consumption levels above the world average. This macro-level trend helps explain the higher operational emissions observed in those countries.

Previous research also highlights the influence of national electricity mixes on building carbon performance (Nematchoua et al., 2020; Rossi et al., 2012). Despite this, the use-stage contribution of the Cambodian reference scenario is comparable to that reported for three detached house types in Thailand (Viriyaroj et al., 2024), one of the few comparable studies conducted in a tropical Southeast Asian context. Extending the comparison to other building typologies, the proportion of use-stage emissions in this study is also similar to the Singapore food-factory case, in which this stage accounted for approximately 85% of total emissions (Kua et al., 2012).

Furthermore, integrating solar energy in the combined scenario reduced annual electricity consumption by approximately 51%, demonstrating its effectiveness as a mitigation strategy. This intervention lowered the overall footprint to 667 kg CO<sub>2</sub>-eq/m<sup>2</sup>, substantially below most reviewed cases that do not incorporate renewable energy systems. By comparison, a design alternative in Vietnam focusing on sanitary and lighting improvements still produced a higher total footprint of 834 kg CO<sub>2</sub>-eq/m<sup>2</sup> (Le et al., 2021).



**Figure 5-17.** Comparison of carbon footprint of the studied townhouse in Cambodia with other building LCA studies in Southeast Asia countries.

The reviewed case studies indicate that the contribution of the production and construction stage to the total life-cycle carbon footprint ranges between 9% and 36%, excluding the low-environmental-impact townhouse in Cambodia and the second design alternative of the office building in Vietnam. Conventional residential buildings in Southeast Asia generally exhibit relatively low embodied carbon shares (9-36%), well below 50%, confirming the dominance of the use stage in tropical contexts. The Cambodian townhouse shows a 14% contribution from the production and construction stage, which is consistent with comparable residential buildings in Thailand. In contrast, the green office building in Vietnam (second scenario) and the low environmental impact townhouse in Cambodia present a substantially higher proportion (57% and 10%, respectively) in production and construction stage, reflecting significantly reduced operational energy demand and a relative shift toward embodied emissions. Moreover, variations in embodied carbon intensity across the reviewed studies can be also influenced by the ratio of material quantities to GFA, which is closely related to building volume, façade surface area, and the design of internal partitions.

### 5.6.8 Limitation of the study

The limitations of this study are primarily related to assumptions concerning data availability and system boundaries. A major limitation lies in the lack of regionally adapted life cycle inventory databases for assessing material-related environmental impacts. To address this gap, on-site measurements and consultations with building professionals and the building owner were conducted to obtain sufficient data on building materials, electricity consumption, and technical characteristics of the case study. Ideally, accurate input data should be derived from detailed architectural and structural drawings, as well as material specifications provided by suppliers. However, such documentation is often unavailable for typical townhouse developments in Cambodia, which are commonly constructed using conventional practices without formal involvement of architects or structural engineers. This significantly constrains the availability and accuracy of technical data. In addition, the adoption and use of Building Information Modeling (BIM) tools to support systematic data collection remain limited and relatively recent in the Cambodian construction sector. The LCA databases and assessment tools were therefore selected based on their widespread use in previous studies. Nevertheless, conducting sensitivity analyses using alternative or same regional material databases would be valuable, as the selection of GHG reduction strategies may be influenced by regional context and database assumptions (Alaux et al., 2024).

Moreover, the end of life stage was not included in this study due to lack of data about building demolition, potential of recyclability of building materials, and transport to disposal site in Cambodia. However, the end of life stage is often very low compared to other life cycle stages (Gardezi et al., 2021; Nematchoua et al., 2022; Sharma et al., 2011). Future studies will include all detailed stages in cradle-to-grave system boundary to deepen the understanding of the different impacts due to each life cycle stage. The authors only know that recyclable materials, such as cardboard, paper, aluminum, tin, and plastics, are collected in local and trafficked to neighbor countries (Cambodianess, 2021). However, the end of life stage is often very low compared to

other stages of the life cycle (Sharma et al., 2011). For example, Nematchoua et al. (2022) showed that the carbon footprint of the end of life stage of a low energy residential building in Belgium is less than 1% of the total life-cycle carbon footprint of the studied building (Nematchoua et al., 2022). In a study of the Malaysian housing sector, it is found that its end of life carbon footprint accounts for 1.8% of the overall buildings carbon footprint (Gardezi et al., 2021).

Nevertheless, carrying out simplified life cycle analyses, linked to the availability of local data, is recognized as useful by various international sources (Wittstock et al., 2012; Decorte et al., 2021; Rossi et al., 2012). Comparing results of complete LCA with results of one-dimensional LCA approach, Decore et al. (2021) showed that the order of preference between different tested scenarios did not change based on the calculation method used, but that the percentage variance between certain scenarios varied (Decorte et al., 2021). We can thus conclude that the approach applied in this research allows us to have a global idea of the effect of several scenarios applied on the carbon footprint and environmental impacts generated by a residential building in Cambodia. It also prioritizes the studied design strategies aiming to reduce impacts in this context, which had never been studied before for this country.

In this study, only a single case study has been used and the strategies assessed are scenario-based, thus this is also a limitation of the study. Lokko et al. (2024) used LCA to compare the different building materials used across 12 major housing typologies in Ghana and Senegal, revealing significant variations in their effectiveness at reducing GHG emissions across different typologies (Lokko et al., 2024). It can be interesting to apply LCA studies on other residential building types in Cambodia such as multi-family buildings and detached houses. However, the case study chosen for this study is considered representative of residential buildings, as it has been primarily constructed in urban areas and is adaptable to the Cambodian context. Taing et al. (2023) found that 61% of people lived in townhouses in Phnom Penh, compared to those in other residential building typologies (Taing et al., 2023). This case study can demonstrate the potential for environmental impact reduction across several residential housing typologies in the country, although the application ratio may vary among different scenarios and building typologies.

To ensure safety, structural integrity, and facilitate the extensive use of timber in residential buildings, particularly regarding strategy 3, which replaces masonry walls with timber structures, it is recommended to further consider the fire resistance and load-bearing characteristics of timber walls as suggested in timber elements (Alinoori et al., 2020; Perković et al., 2024).

## 5.7 CHAPTER CONCLUSION

Building LCA studies are currently lacking for the Cambodian building sector. This research contributes by initiating building LCA practice in Cambodia and by assessing the carbon footprint and broader environmental impacts of residential buildings. The findings support the development of more sustainable strategies for housing in the country. Moreover, the results provide an LCA benchmark for low-income or developing tropical countries in Southeast Asia with similar regional, economic, and climatic conditions.

The building carbon and environmental footprints were calculated from a modeled life-cycle inventory using SimaPro 9.4.0.2 with the ecoinvent v3.8 database, following international standards ISO 14040 and ISO 14044 and the European standard EN 15978. The case study analyzed a townhouse located in Phnom Penh, the capital city of Cambodia. The production, construction, and use stages were considered, and four mitigation strategies were evaluated: 1) material optimization, 2) replacement of conventional materials with low-carbon manufacturing alternatives, 3) adoption of a lightweight timber structural system, and 4) integration of rooftop solar PV panels.

The building produced a carbon footprint of 1261 kg CO<sub>2</sub>-eq/m<sup>2</sup> and an environmental footprint of 125.9 mPt/m<sup>2</sup>. To reduce the carbon footprint throughout the building life cycle, it is necessary to combine at least one strategy concerning the rational use of materials or the choice of more eco-friendly materials with at least one strategy promoting the rational use of energy or local production of renewable energy. In this case study, the two best design strategies are installation of solar PV panels on the roof shelter, then using lightweight timber frames in place of masonry walls. However, the best result was produced by the combined scenario (the sum of all scenarios) generating a carbon footprint reduction of 47% and an environmental footprint reduction of 30%, when compared to the reference scenario.

In conclusion, the results of this research may lead to the integration of the life cycle perspective and low-carbon building strategies in the academic fields and in the framework, assessment tool, and regulation development of green buildings in Cambodia. The defined design strategies can also be used by construction professionals for improving future renovation, refurbishment, and design of new houses in Cambodia, as well as for inspiring public authorities regarding their subsidy policies and construction regulations.

This research opens several perspectives for future studies. First, further life cycle impact assessments should investigate a wider range of alternative low-energy construction materials and renewable energy systems. In addition, other processes contributing to the reduction of building life cycle impacts such as the integration of circular economy principles in construction materials should be explored. Comparing the construction costs of the reference townhouse with those of the proposed scenarios would be particularly valuable in addressing the current demand for affordable housing in Cambodia. Expanding the analysis to include economic feasibility and cost-benefit considerations would enhance the practical relevance of the findings for policymakers, architects, and developers, helping to bridge environmental performance with implementation challenges in a developing-country context.

As this chapter represents an initial exploration of building life cycle assessment in Cambodia, subsequent chapters extend the analysis to additional residential typologies and comparative assessments. Chapter 6 will examine the life cycle environmental performance of a multi-family apartment building, while Chapter 7 will focus on cost-benefit analyses of different scenarios and a comparative evaluation of key environmental impact categories. Furthermore, the development of a Cambodia-specific life cycle inventory database for construction materials is strongly recommended, following approaches already established in many developed countries. Finally,

this study provides a foundation for applying building LCA methodologies in other developing tropical countries with similar climatic and construction contexts.

# 6

## Life cycle assessment of a high-rise apartment building

This chapter performs a full LCA of a high-rise apartment building and the associated strategies introduced in the previous chapter. The LCA follows the same standards, tools, databases, and environmental impact assessment method as applied in the first case study (townhouse), ensuring methodological consistency. The results are presented in detail for the reference scenario, disaggregated by building life cycle stages and modules, as well as by building components and materials. In addition, the results of all scenarios are comparatively analyzed and discussed in terms of their potential improvements in both carbon footprint and total environmental impact, as well as the associated trade-offs.

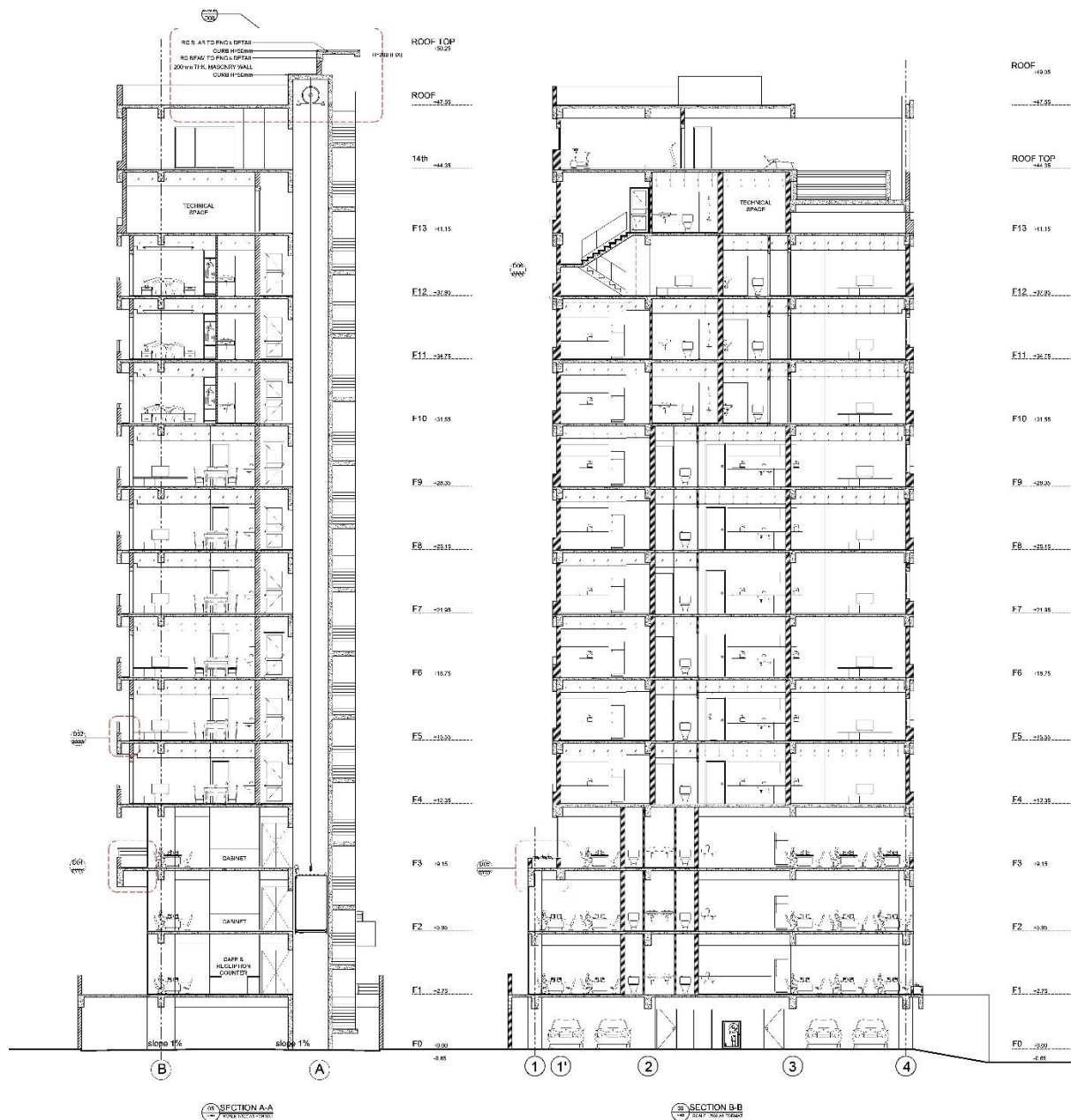
## 6.1 DESCRIPTION OF A HIGH-RISE APARTMENT BUILDING IN CAMBODIA

Apartment Area 11 (see Figure 6-1 left), located in Sangkat Tuol Tumpung 1, Khan Chamkar Mon, Phnom Penh, is a 15-story high-rise residential building. The apartment building was completed by the end of 2022 and residents began to move into the building in November of the same year. This high-rise apartment building constitutes a gross floor area (GFA) of 3,389 m<sup>2</sup>. The architectural, structural, functional, and operational data were obtained from architectural and technical drawing given by the architect who participated in this building project.



**Figure 6-1.** Streetview of the high-rise apartment (left) and apartment unit types (right).

The apartment building is divided into three types of dwelling units namely 1-bedroom unit, 2-bedroom unit, and penthouse. There are 24 units in total. As shown in Figure 6-1 right, the 1-bedroom units are classified into three types: Unit 41, Unit 42, and Unit 43. The 2-bedroom units are classified into two types: Unit 101 and Unit 102. The classification is based on differences in area and functional layout. All units include bedroom, living space, dining space, kitchen, balcony, toilet, and bathroom.



**Figure 6-2.** The architectural section drawings of the apartment.

The facility and programs in the building are one parking floor, three office floors, nine apartment floors, one technical space floor, and one gym with swimming pool floor (Figure 6-2). From the ground to the 1<sup>st</sup> floor, there is one parking space for eight car places and some motorbikes. From 4<sup>th</sup> to 9<sup>th</sup> floor and the 12<sup>th</sup>, there are three dwelling units per story with three bedrooms in each story, one common staircase and one common lift. On the 10<sup>th</sup> and 11<sup>th</sup> floor, there are three dwelling units per story with four bedrooms, one common staircase and lift. There are two dwelling units per story with two bedrooms, technical space under the pool, one common staircase, lift, and kitchen on the 13<sup>th</sup> floor. And, the 14<sup>th</sup> floor comprises of gym room, swimming pool, bar counter, one common staircase and lift, shower, and toilets. The building has two passenger lifts; one can go only up to the 2<sup>nd</sup> floor. The detailed architectural, structural, and

technical plans are attached to the Appendix C. The characteristics and specifications of the building case study are presented in Table 6-1, while the estimated annual electricity and water consumption are described in the following sections.

**Table 6-1.** *Specification of the building case study*

<b>Building case study layout</b>	<b>Specification</b>
Land area [m <sup>2</sup> ]	359.59
Number of floors	15 floors
Number of dwellings	24
GFA [m <sup>2</sup> ]	3,389
Total height [m]	50.25
Number of residents in the year of 2023	53
Annual electricity consumption [kWh]	89,696
Annual water consumption [liters]	2,089,260
Service life	50 years

Regarding the apartment building’s operational energy consumption, the electricity use associated with heating, cooling, ventilation, cold water, and domestic hot water systems is included in the analysis. This consumption is derived from the total monthly electricity bills (see Appendix C) and therefore reflects the energy use during the building’s operational phase. However, specific material data for bathroom accessories, kitchen furniture, and MEP (mechanical, electrical, and plumbing) and HVAC systems were not available in the building’s bills of quantities (BoQ). Consequently, these components were excluded from the material inventory and from the assessment of the environmental impacts. Only their operational energy use, as captured in the electricity bills, is considered.

## **6.2 LIFE CYCLE ASSESSMENT OF THE HIGH-RISE APARTMENT BUILDING**

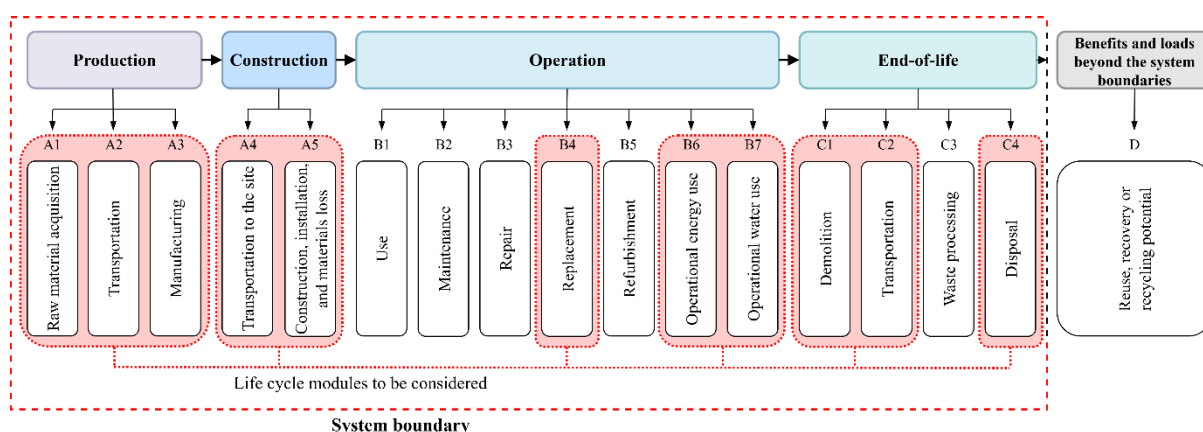
This LCA study of a high-rise apartment building in Cambodia follows ISO 14040 and 14044 standards, including four stages: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO, 2006a, 2006b). The European Standards for LCA of buildings: EN 15978 are also followed for specifying the application of LCA to building level and dividing the life cycle stages and modules of the building (CEN, 2012b).

### **6.2.1 Goal and scope definition**

This study focuses on demonstrating the application of complete LCA on a high-rise residential building, to identify environmentally feasible building design improvement strategies. The building LCA will assess sixteen environmental impact categories. Through the LCIA results interpretation, the significant contributions to the overall impacts will be highlighted and design solutions for the case study will be compared with the original design, referred to reference

scenario. The building design strategies will be proposed based on the comparison results across different scenarios.

The system boundary of this building LCA, illustrated in Figure 6-3, covers the stages from production (A1–A3) and construction (A4–A5) to operation (B4, B6, and B7) and end of life (C1, C2, and C4). The information modules use (B1), maintenance (B2), repair (B3), refurbishment (B5), and waste processing (C3) were excluded due to the unavailability of data and references for the case study. The modules A1 to B4 were categorized in accordance with the EN 15978 standard. Building reference lifespan is required for conducting the building LCA and it is set to be 50 years. The selected functional unit was 1 m<sup>2</sup> of GFA.



**Figure 6-3.** Life cycle stages for the building case study LCA's system boundary.

An LCA model was developed and analyzed using SimaPro version 9.4.0.2, which is recognized as one of the leading software tools for life cycle assessment. The ecoinvent 3 database was used to model the building inventory, accounting for all inputs related to material production (cradle-to-gate), transportation, energy and water use, and the end of life treatment of materials throughout the building life cycle.

## 6.2.2 Life cycle inventory (LCI)

### 1) Production phase

Based on the BoQ obtained from the building architect, the excel of BoQ was used and data of material types and their quantities were retrieved for each building component. The building components included in the study, their materials, and their quantities are listed in Table 6-2. The following assumptions were made in this study:

- The quantities of materials retrieved from the BoQ were assumed to be accurate representations of the existing building.
- The types of materials available in the ecoinvent 3 database are limited compared to the actual materials used in the building. For example, the ceramic tiles used in the case study may differ from those represented in the database in terms of composition and

manufacturing processes. Similarly, the natural stone used in the building may originate from a different source than the one represented in the database.

- The steel trusses used for ceiling supports were modeled as low-alloyed steel, as specific data for steel trusses are not available in the database.
- All paints used in the building were substituted with alkyd paint to represent coating materials in the model.
- Marble production was modelled using the ecoinvent database for natural stone plate production, polished, as a proxy, assuming comparable quarrying and processing operations.

**Table 6-2.** *Materials and quantity of different building components.*

<b>Components</b>	<b>Materials</b>	<b>Quantity</b>	<b>Unit</b>	<b>Quantity/GFA</b>
Foundation piles	Concrete	902.27	m <sup>3</sup>	0.27
	Reinforced steel	57,399.69	kg	16.94
Structures (flooring, columns, beams, core wall, and ramp)	Concrete	1,097.88	m <sup>3</sup>	0.32
	Reinforced steel	174,598.19	kg	51.52
Walls	Clay brick	488,089.28	kg	144.02
	Cement mortar	176,784.60	kg	52.16
	Flat glass, coated	2,524.63	kg	0.74
Windows	Aluminium frame	69.16	m <sup>2</sup>	0.02
	Flat glass, coated	8,046.36	kg	2.37
Doors	Aluminum alloy	6,494.62	kg	1.92
	Flat glass, coated	2,285.50	kg	0.67
	Wood	69.60	m <sup>2</sup>	0.02
	Polyvinylchloride	2,235.60	kg	0.66
Staircases	Concrete	36.70	m <sup>3</sup>	0.01
	Reinforced steel	5,693.11	kg	1.68
	Aluminium frame	17.29	m <sup>2</sup>	0.01
	Flat glass, coated	1,712.91	kg	0.51
	Steel, low-alloyed	518.68	kg	0.15
Finishing	Gypsum plasterboard	131.40	kg	0.04
	Ceramic tile	119,212.68	kg	35.18
	Steel, low-alloyed	566.00	kg	0.17
	Alkyd paint	1,230.40	kg	0.36
	Natural stone plate	3,519.20	kg	1.04
	Base plaster	97,697.00	kg	28.83

The building foundation includes bored piles and pile caps. External walls are mostly built up in mostly masonry and a single-glazed glass façade installed at curtain walls around the office floors. Internal walls built up in different thickness, are mostly made of masonry, glazed partition, with

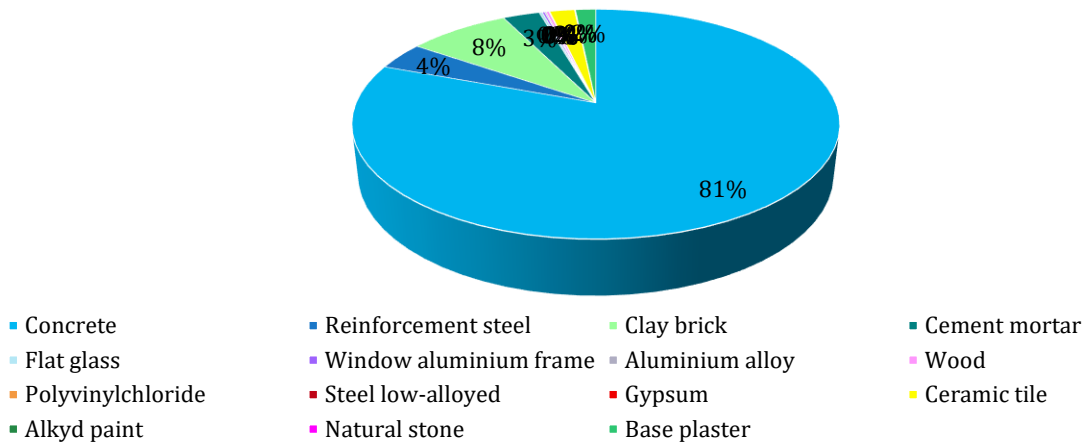
wooden doors. In this building, four distinct types of doors were employed, classified according to their primary constituent materials: laminated tempered glass doors, wooden doors, aluminum doors, and polyvinyl chloride (PVC) panel doors. These four door specifications were further divided into several subtypes according to their dimensions. The windows were predominantly composed of laminated tempered glass combined with aluminum framing systems. The curtain wall system was considered as the same building component as the windows in terms of material composition and functional characteristics, with the only distinction being its larger scale and its role as a continuous façade element. Windows and curtain walls were further classified into several types according to their sizes and positions within the building. Reinforced concrete was utilized in load-bearing structures (floorings, columns, beams, core wall, and ramp), staircases, car and motorbike parks, and foundation piles. Staircases were enveloped by numerous hexagonal shaped glasses with and without colored as seen in Figure 6-1 left.

The production stage considered overall impacts from raw materials extraction and processing, transportation of materials to the factory, and manufacturing of materials to products.

**Table 6-3.** *Mass and percentage share of construction materials used in the building case study.*

<b>Material</b>	<b>Mass [kg]</b>	<b>Percentage of total mass [%]</b>
Concrete	4,888,453.17	80.62
Reinforcement steel	237,691.00	3.92
Clay brick	488,089.28	8.05
Cement mortar	176,784.60	2.92
Flat glass	14,569.39	0.24
Window aluminium frame	11,681.68	0.19
Aluminium alloy	6,494.62	0.11
Wood	14,616.00	0.24
Polyvinylchloride	2,235.60	0.04
Steel low-alloyed	1,084.68	0.02
Gypsum	131.40	0.002
Ceramic tile	119,212.68	1.97
Alkyd paint	1,230.40	0.02
Natural stone	3,519.20	0.06
Base plaster	97,697.00	1.61
<b>Total</b>	<b>6,063,490.69</b>	<b>100</b>

The Table 6-3 presents the mass and percentage contributions of construction materials to total mass. In Figure 6-4, concrete alone accounts for almost 81%, following by clay brick 8%, reinforcement steel 4%, cement mortar 3%, and ceramic tiles 2% of total mass. The combination of the materials used in structures: concrete and reinforcement steel together was about 85% of the total material mass. The envelope materials: clay brick, cement mortar, and flat glass contributed about 11%, while finishing materials contributed about 4% which most shared from ceramic tiles and base plaster.



**Figure 6-4.** Percentage contributions of construction materials used in the building.

## 2) Construction phase

The construction stage covers the impacts from materials transportation to the building construction site and materials losses during the construction and installation into the building process. The transport distances from the factory to the construction site were assumed to be 300 km for all materials types and 50 km for concrete (Abd Rashid et al., 2017; Wittstock et al., 2012). For the transportation type, a 16-ton lorry was assumed for the delivery of materials from the factory to the construction site, whereas a 24-ton lorry was assumed for the transportation of concrete. The addition of 5% of materials loss during construction was considered from the total building materials.

## 3) Operational phase

### a) Operational energy

Electricity is the only one operational energy consumption required for functioning and operating the building. It includes the energy for air conditioning, lighting, lift, and appliances. There is not any data to be found and provided for energy consumption of parking, office, apartment dwelling, gym and swimming pool, cooling, lighting, lift, and other appliances. The annual electricity consumption was estimated in 2023 based on the monthly record of the electricity bills sent from Electricité du Cambodge. The electricity consumption of the whole building based on actual data is 89,696 kWh.

### b) Operational water

Notice that the permission of data collection from the building case studies in Cambodia is strict and partially allowed because the owner is concerned about how their building data is used or evaluated and their insecurity. For the water consumption, data from Phnom Penh Water Supply Authority's report calculated that Phnom Penh residents on average consume 108 liters/capita/day of water (Phnom Penh Water Supply Authority, 2022). This data will be used for

estimating the water consumption within the building. Given that there are 53 residents, the annual water consumption will be 2,089,260 liters.

### **c) Replacement and maintenance**

Replacement data were included only for selected building components expected to undergo renewal during the building's lifespan. Painting, windows, and solar photovoltaic (PV) panels were considered in this life cycle stage. The replacement frequencies were assumed to be four times for painting, once for windows, and once for solar PV panels over a 50-year building lifespan, ensuring proper building functionality and condition.

### **4) End of life phase**

In the end of life phase, the building case study is assumed to be demolished mechanically using equipment powered by diesel fuel. The energy consumption for demolition activities (module C1) was estimated at 0.061 MJ/kg for the concrete structural frame, based on Gervasio et al. (2018) (Gervasio & Dimova, 2018). According to Kumanayake et al. (2018), the transport distance of waste materials from the demolition site to the landfill (module C2) was assumed to be 15 km, using a 20-ton lorry for transportation (Kumanayake & Luo, 2018). The demolished building waste was assumed to be transported entirely to landfill, as Cambodia currently lacks large-scale waste recycling facilities (Pheakdey et al., 2022). Therefore, module C3 (waste processing for reuse or recycling) was excluded from the scope of this study. Thus, module C3 is not included in this scope of work. The landfilling impact (module C4) was calculated using the ecoinvent process data and the actual material quantities. Due to limitations in the available material types in the database, materials other than steel, concrete, paint, gypsum, cement, aluminium, PVC, wood, glass, and plaster were classified as inert waste for final disposal.

### **6.2.3 Life cycle impact assessment (LCIA)**

After collecting the life cycle inventory data for each stage, the building LCIA was conducted in accordance with the EN 15804+A2 standard. The most recent revision of this standard (A2, 2019) aligns with the European Commission's Environmental Footprint (EF) methodology. Therefore, the EN 15804+A2 standard applies the EF v3.0 method, which includes sixteen environmental impact indicators available in the SimaPro v9.4.0.2 software. Accordingly, the environmental impacts of the high-rise apartment in this study were assessed using the EF v3.0 impact categories, as listed in Table 5-3. The EF method was selected for this assessment because it provides a more comprehensive evaluation than the CML (Centre of Environmental Science) method used in the earlier EN 15804+A1 standard (Mirzaie et al., 2020).

In LCA studies, a single-score indicator helps to simplify the overall environmental impact assessment by aggregating multiple impact categories, each with different measurement units, into a single total score. This score is obtained by first normalizing the characterized results, then weighting the sixteen impact categories, and finally combining the weighted outcomes. The

weighted value is calculated by multiplying the normalized results by their respective weighting factors (Sala et al., 2018).

The relationship among these parameters is expressed as follows:

$$\text{Single score} = \sum_1^i CV_i \times NF_i \times WF_i \times 1000$$

where  $CV_i$  is the characterized value,  $NF_i$  is the normalization factor, and  $WF_i$  is the weighting factor for impact category  $i$ . The normalization and weighting factors ( $NF_i$  and  $WF_i$ ) are provided in Table 5-4.

#### 6.2.4 Interpretation

The LCIA results are interpreted according to the goal and scope definition of the study. The results of the assessed scenarios and the considered elements namely, the life cycle stages, building components, and materials are compared and discussed to identify their relative significance across the sixteen environmental impact categories.

#### 6.2.5 Building design strategies

The building design strategies were selected based on on-site investigation, consultation with the project architect, and insights from the literature. The proposed strategies aim to reduce environmental impacts while aligning with the country's carbon reduction targets. Wherever possible, best-practice approaches and scenarios were applied. Each strategy was modeled based on the existing building, and the results are presented in the following section.

##### 1) Strategy 1: minimize unnecessary/decoration materials

Strategy 1 is a feasible approach aimed at removing natural stone materials from decorative elements in the living room and bathroom. The purpose of this strategy is to reduce the extraction and use of mineral and natural materials, which are typically applied in large quantities in this building type. In residential buildings of the same typology, these materials are also commonly used in similar or even greater quantities. In the case study building, natural stone was primarily used for finishing, including the bathroom sink counter and cupboard decorations in the living room (Figure 6-5). By removing these materials, plaster and paint can be applied as alternative coatings for finishing. This strategy reduces approximately 3.5 tons of building materials.



**Figure 6-5.** *Natural stone used for decoration in the bathroom (left) and living room (right).*

## **2) Strategy 2: use environmental manufacturing process and bio-based materials**

Strategy 2 aims to replace the existing reinforced concrete CEM II/A (density 2,370 kg/m<sup>3</sup>) with reinforced concrete CEM II/B of the same density. The U-values of the existing and new flooring materials were compared to evaluate energy efficiency, given that detailed energy consumption simulations were not performed in this study. The flooring thickness is 120 mm on every story.

The U-value for both types of concrete is identical at 12.92 W/m<sup>2</sup>K. In general, CEM II/B concrete contains more mineral additives and less clinker than CEM II/A, making it more sustainable and reducing CO<sub>2</sub> emissions. The LCIA results from this replacement affect only the production stage, with no changes in operational energy.

Comparing U-values ensures that the new material performs at least as well thermally as the existing material. Therefore, if the new U-value is comparable or lower than the original, the strategy is considered acceptable. This replacement applies to all reinforced concrete components, including floors, beams, columns, core walls, ramps, and staircases.

Additionally, Strategy 2 replaces aluminium window frames with wood frames to increase the use of renewable materials. The U-values for aluminium and wood frames are 1.6 and 1.5 W/m<sup>2</sup>K, respectively, indicating comparable thermal performance. All existing window and curtain wall frames are replaced under this strategy.

The U-values of the building components were calculated using the formula below. The thermal properties of the building materials, including the thermal conductivity coefficient ( $\lambda$ , W/m·K) and thermal resistance (R-value, m<sup>2</sup>K/W), are presented in Table 6-4.

$$U_{\text{value}}(\text{building component}) = 1 \div R_{\text{T}}$$

where  $R_{\text{T}}$  is the total thermal resistance (R-value) of all material layers within the building component.

**Table 6-4.** Thermal properties of the building materials.

Building materials of the walls	Thickness [m]	Thermal conductivity coefficient $\lambda$ [W/mK]	Thermal resistance R [m <sup>2</sup> K/W]
Reinforced concrete <sup>1</sup>	0.12	1.55	0.08
Clay hollow brick <sup>1</sup>	0.1	0.52	0.19
	0.15	0.52	0.29
Cement mortar <sup>1</sup>	0.01	1.15	0.01
Base plaster <sup>2</sup>	0.005	0.35	0.01
External surface <sup>3</sup>	-	-	0.04
Sheathing board <sup>3</sup>	0.01	0.13	0.08
Air cavity <sup>3</sup>	0.14	-	0.18
Timber <sup>3</sup>	0.14	0.12	1.17
Internal surface <sup>3</sup>	-	-	0.13

<sup>1</sup>National Technical Regulation on Energy Efficiency Buildings, Vietnam: QCVN 09:2017/BXD (Construction Technique Institute-VASECT, 2017).

<sup>2</sup>Thermal conductivity value of gypsum-based plaster in (Buratti et al., 2014).

<sup>3</sup>Worked examples of U-value calculations using the Combined Method (The Scottish Government, 2020).

### 3) Strategy 3: lightweight timber structure

Strategy 3 aims to replace brick masonry walls with lightweight timber frame walls. The timber wall has a total thickness of 160 mm, consisting of 10 mm sheathing boards on both sides, timber studs (0.02436 m<sup>3</sup>), and timber girders (0.00364 m<sup>3</sup>) per 1 m<sup>2</sup> of wall, along with staples, and no insulation materials.

This replacement applies to all external masonry walls with a thickness of 200 mm and internal masonry walls of 150 mm and 100 mm. Walls adjacent to the kitchen and bathroom, as well as load-bearing walls with thicknesses of 200 mm, 250 mm, and 300 mm, remain unchanged.

The U-value of the walls is improved from 2.38 W/m<sup>2</sup>K for masonry walls to 1.76 W/m<sup>2</sup>K for timber frame walls. The U-value calculation is based on the R-values listed in Table 6-4, with detailed calculation methods provided in Appendix C.

### 4) Strategy 4: renewable energy utilization

Strategy 4 aims to install solar photovoltaic (PV) panels on the roof, west-oriented stair envelope, and south-oriented rear balcony. The PV panels selected are monocrystalline, with a maximum power output of 380 W, dimensions of 1769 × 1052 × 35 mm, weight of 20.5 kg, and a lifespan of 25 years. By weight, each panel is composed of approximately 76% glass, 10% plastic polymer, 8% aluminum, 5% silicon, 1% copper, and less than 0.1% silver and other metals (Union of Concerned Scientists, 2022).

A total of 352 PV panels is installed. The building location receives an average of 5 peak sun hours per day, resulting in a total generation capacity of 133.76 kW. Assuming a panel efficiency of 20% (EcoWatch, 2022), the estimated annual solar energy production is 48,822.40 kWh/year, covering approximately 54% of the building's annual electricity consumption.

The strategy was modeled by including both the annual solar energy input to offset operational electricity demand and the embodied carbon and energy associated with PV panel manufacturing in the production stage.

### **5) Strategy 5: combined strategy**

In this strategy, all of the previously described strategies are combined to analyze their cumulative effects and to identify both positive and negative impacts across the different environmental indicators. Additionally, the overall carbon footprint and environmental footprint are compared between the reference scenario and the combined strategy.

## **6.3 LCA RESULTS**

This section presents the LCA results of a high-rise apartment building in Cambodia. The results were calculated in accordance with the methodological rules of the CEN EN 15804+A2 standard and the guidelines of the EF 3.0 method, including characterization, normalization, and weighting factors. The section identifies and discusses the different environmental impacts, presented through relevant environmental indicators by life cycle modules and stages, building components, construction materials, and the comparison between the existing condition and the studied design scenarios.

### **6.3.1 Impact assessment by life cycle modules and stages**

Table 6-5 shows the total LCIA results of a high-rise apartment building for a 50-year lifespan and for the functional unit of 1 m<sup>2</sup> of building's GFA. The impact shares from different life cycle modules and stages are presented in terms of different impact categories. Operation stage of the building life cycle shares the highest impact on almost all environmental impact categories compared to other stages. Following by the production stage, it is the 2<sup>nd</sup> highest impact shared in most of impact categories compared to other stages. The construction and end of life stage have the lowest overall environmental impact.

Carbon footprint, represented by the climate change (GWP) impact category, was selected for presentation in this section as it provides a clear and widely recognized indicator of environmental performance. In developing countries, carbon emissions, embodied carbon, and climate change are among the most familiar and discussed topics within the construction sector. This reflects the global and regional urgency for carbon emission research and mitigation, particularly in Asia, where many countries have initiated low-carbon projects in the building construction sector.

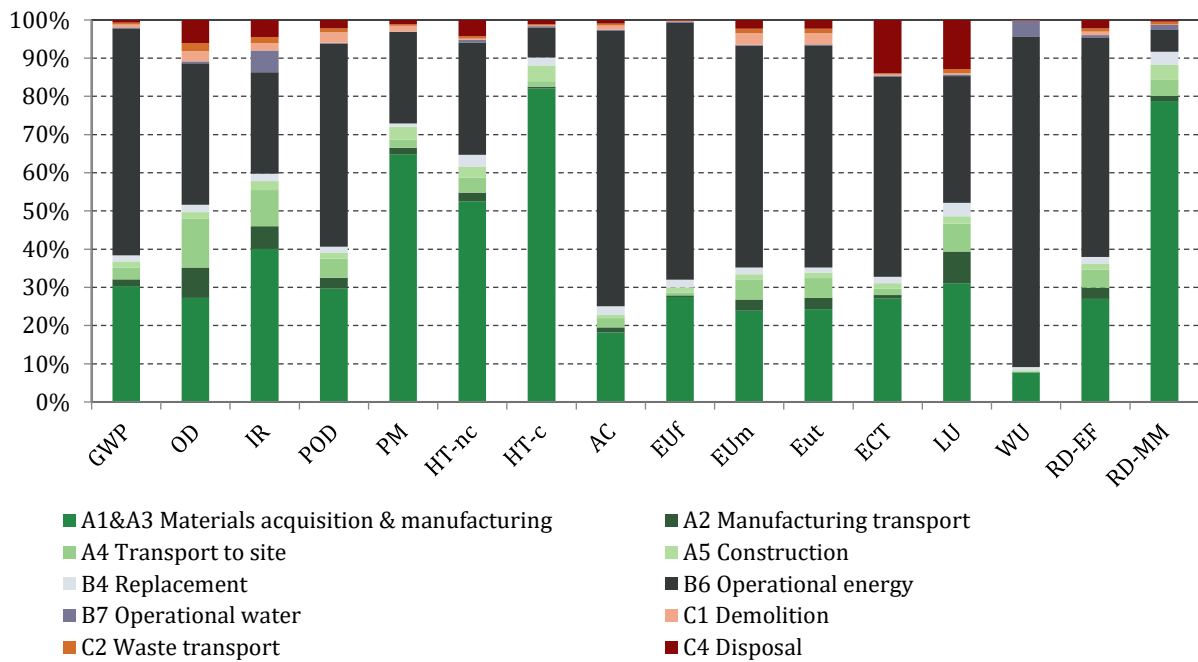
For GWP impact, materials acquisition and manufacturing (A1 and A3) contributed 347 kg CO<sub>2</sub>-eq/m<sup>2</sup> and transport of virgin materials to the factory gate (A2) contributed 21 kg CO<sub>2</sub>-eq/m<sup>2</sup>. Thus, the production stage contributed 368 kg CO<sub>2</sub>-eq/m<sup>2</sup> in total. The construction stage shared overall 53 kg CO<sub>2</sub>-eq/m<sup>2</sup> coming from transportation to construction site (A4) 35 kg CO<sub>2</sub>-eq/m<sup>2</sup> and construction installation with materials loss (A5) 18 kg CO<sub>2</sub>-eq/m<sup>2</sup>. In operation stage, replacement (B4), operational energy use (B6), and operational water use (B7) shared 18, 680, and 3 kg CO<sub>2</sub>-eq/m<sup>2</sup>, respectively. In total, the operation stage shared 701 kg CO<sub>2</sub>-eq/m<sup>2</sup>. During end of life stage, building demolition (C1), waste transportation to the landfill (C2), and disposal (C4) shared 8, 6, and 8 kg CO<sub>2</sub>-eq/m<sup>2</sup>, respectively. The end of life stage contributed overall 22 kg CO<sub>2</sub>-eq/m<sup>2</sup>. Therefore, the high-rise apartment in this study made 1144 kg CO<sub>2</sub>-eq/m<sup>2</sup> to GWP impact.

As shown in Figure 6-6, the contribution from different life cycle stages were divided into modules and illustrated based on the total LCIA results. The operation stage has the highest impact on operational water use (WU) 92% and acidification (AC) 75% compared to other stages. The production stage has the highest impact on human toxicity, cancer (HT-c) 83% and resource use, minerals and metals (RD-MM) 80% compared to others categories. Although the construction and end of life stages do not show an overall significant impact, they demonstrate the highest influence on ozone depletion (ODP) and ionizing radiation (IR), and on ecotoxicity, freshwater (ECT) and land use (LU) impacts, respectively. Modules A1 & A3 and B6 are the top contributors to almost all impacts. These three modules together shared over 60% of all impacts compared to other modules. The modules A1 & A3 and B6 individually contribute an average of 37% and 46% of the total result in each impact category, respectively. This is due to the large quantity of construction materials used for constructing a high-rise residential building and the use of high percentage of coal in the electricity generation mix in Cambodia. Over 90% of climate change (GWP), HT-c, AP, eutrophication, freshwater (Euf), and WU emissions, and over 80% of photochemical ozone formation (POD), particulate matter (PM), human toxicity, non-cancer (HT-nc), eutrophication marine (Eum), eutrophication terrestrial (Eut), resource use fossils (RD-EF), and resource use minerals and metals (RD-MM) emissions are coming from A1 & A3 and B6 modules combined. During the construction stage, most emissions arise from material transportation to the site (A4), while in the end of life stage, they primarily result from the disposal of demolition waste to landfill (C4).

Figure 6-6 also shows that operational water use (B7) and waste materials transport to landfill (C2) are less important factor in this case study as it contributes less than averagely 1% in each impact category. The data inputs for these two modules are based on references; therefore, their impacts may vary and can exceed 1% if water demand increases during prolonged dry seasons or if the demolition site is located more than 15 km from the landfill or far from the city center of Phnom Penh.

**Table 6-5.** LCIA results from each life cycle modules in different impact categories.

Impact category	Unit/m <sup>2</sup>	Production		Construction		Operation			End of life			Total
		A1 & A3	A2	A4	A5	B4	B6	B7	C1	C2	C4	
GWP	kg CO <sub>2</sub> eq	3.47E+02	2.10E+01	3.52E+01	1.84E+01	1.76E+01	6.80E+02	3.32E+00	8.09E+00	5.77E+00	8.28E+00	1.14E+03
OD	kg CFC11 eq	1.73E-05	5.04E-06	8.05E-06	1.11E-06	1.22E-06	2.35E-05	2.82E-07	1.73E-06	1.31E-06	3.85E-06	6.33E-05
IR	kBq U- <sup>235</sup> eq	9.71E+00	1.43E+00	2.31E+00	5.57E-01	4.81E-01	6.44E+00	1.37E+00	4.73E-01	3.78E-01	1.09E+00	2.42E+01
POD	kg NMVOC eq	1.22E+00	1.19E-01	2.04E-01	6.69E-02	6.06E-02	2.19E+00	9.51E-03	1.12E-01	4.33E-02	8.97E-02	4.11E+00
PM	disease inc.	9.68E-05	2.52E-06	3.30E-06	4.96E-06	1.28E-06	3.57E-05	1.94E-07	2.25E-06	5.79E-07	1.67E-06	1.49E-04
HT-nc	CTUh	6.48E-06	2.81E-07	4.87E-07	3.38E-07	3.88E-07	3.64E-06	7.33E-08	4.71E-08	8.51E-08	5.17E-07	1.23E-05
HT-c	CTUh	1.14E-06	7.10E-09	1.98E-08	5.74E-08	2.84E-08	1.10E-07	4.56E-09	2.51E-09	3.76E-09	1.60E-08	1.39E-06
AC	mol H <sup>+</sup> eq	1.42E+00	1.06E-01	1.86E-01	7.65E-02	1.67E-01	5.64E+00	2.46E-02	8.40E-02	3.77E-02	7.57E-02	7.82E+00
EUf	kg P eq	1.05E-02	1.44E-04	2.74E-04	5.30E-04	7.59E-04	2.56E-02	1.78E-04	2.68E-05	4.69E-05	5.50E-05	3.80E-02
EUm	kg N eq	2.93E-01	3.62E-02	6.48E-02	1.65E-02	2.19E-02	7.13E-01	2.80E-03	3.72E-02	1.43E-02	2.86E-02	1.23E+00
EUt	mol N eq	3.33E+00	3.99E-01	7.14E-01	1.86E-01	1.85E-01	7.96E+00	3.27E-02	4.08E-01	1.57E-01	3.13E-01	1.37E+01
ECT	CTUe	6.98E+03	2.57E+02	4.27E+02	3.62E+02	4.37E+02	1.36E+04	7.24E+01	6.49E+01	7.07E+01	3.60E+03	2.58E+04
LU	Pt	1.41E+03	3.76E+02	3.31E+02	8.94E+01	1.57E+02	1.51E+03	1.94E+01	1.41E+01	5.09E+01	5.84E+02	4.54E+03
WU	m3 depriv.	8.05E+01	1.13E+00	1.70E+00	4.08E+00	8.27E+00	9.08E+02	4.42E+01	1.74E-01	2.85E-01	8.09E-01	1.05E+03
RD-E&F	MJ	3.04E+03	3.29E+02	5.31E+02	1.69E+02	2.09E+02	6.45E+03	8.20E+01	1.11E+02	8.70E+01	2.52E+02	1.13E+04
RD-MM	kg Sb eq	2.80E-03	4.84E-05	1.48E-04	1.43E-04	1.20E-04	2.04E-04	4.67E-05	4.16E-06	2.62E-05	1.56E-05	3.56E-03



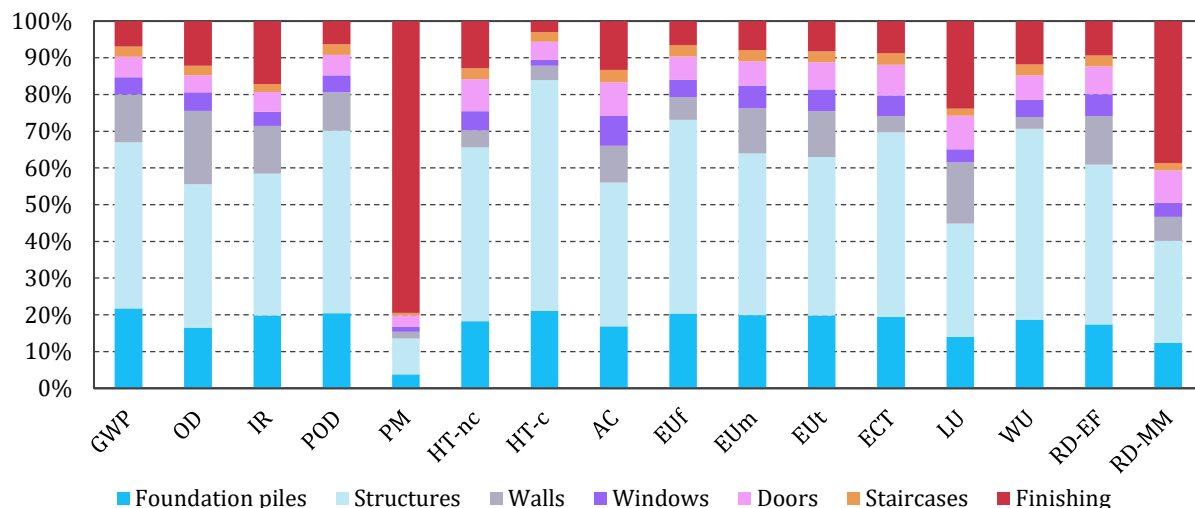
**Figure 6-6.** Environmental impact contribution by each module in different impacts.

### 6.3.2 Impact assessment by building component

Material manufacturing embodied impacts and operational energy use impacts are the two top contributors for almost every impact category, according to results presented in Table 6-5 and Figure 6-6. Therefore, this highlighted that the design should focus on these stages to efficiently improve the building emission improvement. The results can also report to the professionals in construction sector that assist them to address and understand simply the most critical impact contributors on the design options.

In the Figure 6-6, the construction materials used is one of the most influential contributors to LCIA results. To optimize material usage and understand its impact, for example during building design, it is necessary to analyze the detailed allocations of materials used in different building components. Figure 6-7 illustrates that each building component shared more or less similar allocations to the results of each impact category except the finishing. The structures (included flooring, columns, beams, core walls, and ramp), foundation piles, and finishing are the top three building components that individually contribute an average of 42%, 18%, and 17% of the overall results in each impact category, respectively. The attention should focus on these three components and materials involved, according to the impact of quantity of material consumption and their high embodied carbon. Walls and doors represent the second group of components requiring attention, contributing on average 9% and 7% to the total impacts, respectively. Although windows, including curtain walls, represent only 0.003% of the total material mass, they contribute on average 5% to the overall impacts and therefore require consideration. Staircases is the component that contributes the least to the total results, averagely only 3%, mainly due to having the least material quantity used in this assembly. Table 6-2 presents the detailed

configurations of materials and quantities for each building component. Understanding the impact contributions of different material types is important, as both the type and amount of construction materials vary across components. These results are presented in detail in the following section.



**Figure 6-7.** LCA results of building components in different impact categories.

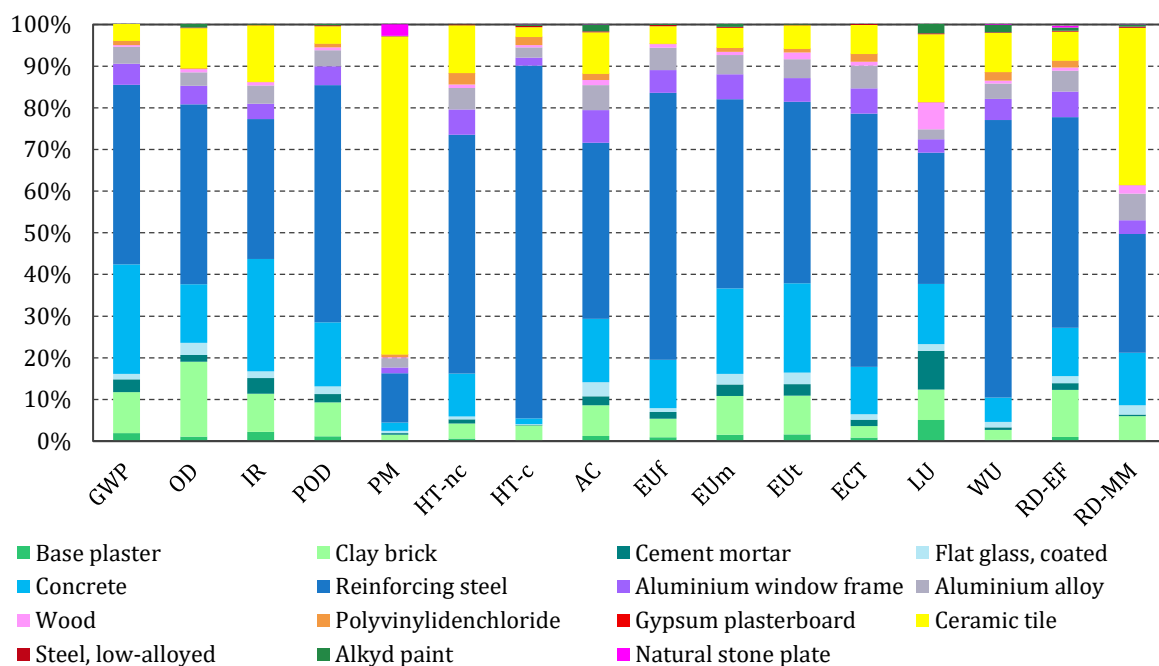
### 6.3.3 Impact assessment by construction materials

Figure 6-8 illustrates the LCA results in terms of construction material types in different impact categories. Reinforcing steel and concrete are the two dominant materials in the LCA results, together contributing an average of 58-86% of the total impacts, except in the LU, RD-MM, and PM categories, where their combined contribution is less than 50%. In particular, for PM, these two materials account for only 14% of the total impact, whereas finishing materials are the major contributor, responsible for 76% of the total. LU impacts are typically influenced when wood is extensively used in building construction, as this requires forestry activities.

Reinforcing steel is the highest impact contributor, in average 48% of total impacts, although it is only the third-largest material by quantity used in the apartment construction. This highlights that environmentally friendly alternatives to this material could be advantageous. Reinforcing steel is the primary material for concrete reinforcement due to its high strength, but its production is energy and carbon intensive as well as costly. Recent studies suggest bamboo as a potential alternative for certain concrete components; however, its strength and durability remain uncertain, and its use in multi-story or long-lifespan structures is still challenging (Dhiman & Lallotra, 2021; Javed et al., 2024). However, fiber reinforced polymer can also be the option among alternatives. Concrete materials include structural elements such as flooring, columns, beams, core walls, ramps, and foundations. Concrete accounts for 81% of the total material weight of the building, the largest share among all materials, while its LCA impact contribution ranges from 1–27% across different impact categories. On average, concrete contributes 14% to the impacts,

ranking as the third-highest impact material despite being the most widely used by quantity. Nevertheless, its life cycle impacts remain significant in reinforced concrete buildings.

Besides reinforcing steel and concrete, ceramic tiles and clay bricks should also be investigated. Ceramic tiles account for 2% of the total material mass, with an impact contribution ranging from 2-76% across categories, averaging 14%. Clay bricks represent 8% of the total material mass representing the second-highest by quantity, while their impact contribution ranges from 1-18%, averaging 7%.



**Figure 6-8.** LCA results of building construction materials in different impact categories.

### 6.3.4 Carbon footprint assessment of the apartment building and different scenarios

Table 6-6 presents the characterized results for all scenarios across the different environmental impact categories. These values were used to calculate the single score results of each scenario, as shown in Table 6-7. Detailed values for characterized, normalized, and weighted results for all scenarios, impact categories, and building life cycle stages are provided in Appendix D as supplementary data. The results in Table 6-6 are also used for comparisons presented in Figure 6-9 and Figure 6-10.

**Table 6-6.** Accumulated LCIA results over the building's life cycle by impact category of each scenario.

Impact category	Unit/m <sup>2</sup>	Reference	Strategy 1	Strategy 2	Strategy 3	Strategy 4
GWP	kg CO <sub>2</sub> eq	1.14E+03	1.14E+03	1.11E+03	1.12E+03	8.72E+02
OD	kg CFC11 eq	6.33E-05	6.00E-05	6.22E-05	6.19E-05	6.29E-05
IR	kBq U- <sup>235</sup> eq	2.42E+01	2.32E+01	2.38E+01	2.38E+01	2.52E+01
POD	kg NMVOC eq	4.11E+00	4.03E+00	4.04E+00	4.07E+00	3.33E+00

PM	disease inc.	1.49E-04	1.45E-04	1.48E-04	1.49E-04	1.37E-04
HT-nc	CTUh	1.23E-05	1.23E-05	1.18E-05	1.21E-05	1.49E-05
HT-c	CTUh	1.39E-06	1.39E-06	1.37E-06	1.38E-06	1.43E-06
AC	mol H <sup>+</sup> eq	7.82E+00	7.75E+00	7.69E+00	7.78E+00	5.46E+00
EUF	kg P eq	3.80E-02	3.80E-02	3.74E-02	3.81E-02	2.90E-02
EUm	kg N eq	1.23E+00	1.20E+00	1.20E+00	1.21E+00	9.59E-01
EUt	mol N eq	1.37E+01	1.34E+01	1.34E+01	1.35E+01	1.07E+01
ECT	CTUe	2.58E+04	2.57E+04	2.53E+04	2.57E+04	2.20E+04
LU	Pt	4.54E+03	4.09E+03	5.10E+03	6.22E+03	4.41E+03
WU	m3 depriv.	1.05E+03	1.05E+03	1.05E+03	1.05E+03	6.06E+02
RD-E&F	MJ	1.13E+04	1.10E+04	1.11E+04	1.11E+04	9.05E+03
RD-MM	kg Sb eq	3.56E-03	3.54E-03	3.50E-03	3.52E-03	1.02E-02

Figure 6-9 present the comparison of climate change (GWP), defined as the carbon footprint, for the reference scenario and four studied design strategies across different building life cycle stages. The reference scenario represents the existing condition of the high-rise apartment building. The GWP impacts for the reference case, Strategy 1, Strategy 2, Strategy 3, and Strategy 4 are 1144, 1136, 1113, 1117, and 872 kg CO<sub>2</sub>-eq/m<sup>2</sup>, respectively. Strategy 1, which aims to minimize the use of unnecessary finishing materials, reduces the overall carbon footprint by approximately 1% compared to the reference scenario. Strategy 2 and Strategy 3 achieve reductions of 3% and 2%, respectively, while Strategy 4 results in a substantial reduction of up to 24% compared with the reference.

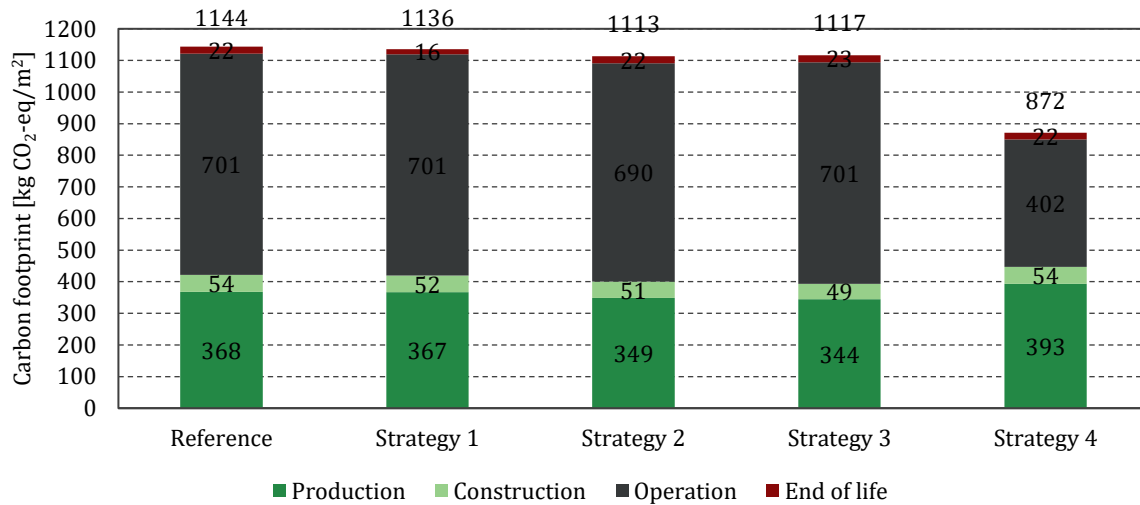
From a life cycle perspective focused on the production stage, Strategy 2 shows a greater reduction in carbon footprint than Strategies 1 and 3, achieving about a 5% decrease compared to the reference. In contrast, Strategy 4 adds approximately 7% more impact in this stage due to additional materials required for the PV system.

As observed in Figure 6-7, further improvement in the carbon footprint could be achieved in Strategies 1 and 3 by reducing ceramic tiles in finishing materials and incorporating more timber components, not only in external walls but also in elements such as doors, windows, staircases, and structural components. Similarly, for Strategy 2, additional reductions could be explored by substituting conventional materials with more eco-friendly alternatives, such as low-carbon or green concrete made with less cement and or recycled aggregates, although these materials remain limited in the local construction market.

Regarding the operation stage, Strategy 4 shows a significant reduction in carbon footprint compared to the reference and other scenarios. This benefit could be further enhanced if additional PV panels were installed and better integrated into the building design. However, this approach may pose challenges related to local perceptions of façade aesthetics.

The construction and end of life stages show comparatively lower impacts than other life cycle stages. However, Strategy 1 results in a slightly smaller reduction in the end of life stage compared

to other scenarios. This is attributed to the removal of natural stone from finishing materials, which reduces waste generation and disposal to landfill.



**Figure 6-9.** Comparison of GWP results of all scenarios in different building life cycle.

### 6.3.5 Environmental footprint assessment of the apartment building and different scenarios

Table 6-7 presents the single score results for all scenarios across the different environmental impact categories. The single score results for all scenarios, considering each impact category and building life cycle stage, are provided in Appendix D. These results were calculated according to the formula described in Section 6.2.3.

**Table 6-7.** Accumulated environmental footprint total score results over the building's life cycle by impact category of each scenario.

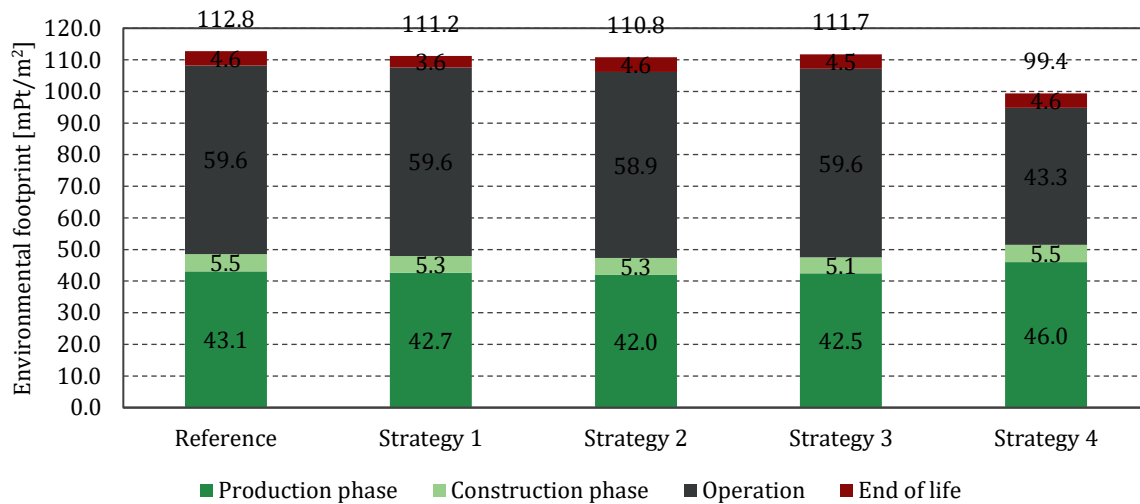
Impact category	Reference	Strategy 1	Strategy 2	Strategy 3	Strategy 4
GWP [mPt/m <sup>2</sup> ]	29.8	29.4	28.4	28.9	22.6
OD	0.1	0.1	0.1	0.1	0.1
IR	0.3	0.3	0.3	0.3	0.3
POD	4.8	4.7	4.7	4.8	3.9
PM	22.5	21.8	22.2	22.4	20.6
HT-nc	1.0	1.0	0.9	1.0	1.2
HT-c	1.8	1.7	1.7	1.7	1.8
AC	8.7	8.6	8.5	8.7	6.1
Euf	0.7	0.7	0.6	0.7	0.5
EUm	1.9	1.8	1.8	1.8	1.4
EUt	2.9	2.8	2.8	2.8	2.2
ECT	11.6	11.5	11.3	11.5	9.9

LU	0.4	0.4	0.5	0.6	0.4
WU	7.8	7.8	7.8	7.8	4.5
RD-E&F	14.4	14.1	14.1	14.3	11.6
RD-MM	4.2	4.2	4.1	4.2	12.1
<b>Total</b>	<b>112.8</b>	<b>111.2</b>	<b>110.8</b>	<b>111.7</b>	<b>99.4</b>

Figure 6-10 present a comparison of the environmental footprint single scores for all scenarios across different building life cycle stages. The single score was calculated using the formula and weighting factors described in Section 6.2.3. This approach allows for a holistic comparison of various design strategies applied to the same or different buildings. The reference scenario and Strategies 1, 2, 3, and 4 yielded single scores of 112.8, 111.2, 110.8, 111.7, and 99.4 mPt/m<sup>2</sup>, respectively. Compared with the reference scenario, the reductions in total single score are approximately 1% for Strategy 1, 2% for Strategy 2, 1% for Strategy 3, and 12% for Strategy 4. Overall, Strategy 4 achieves the greatest reduction in total environmental footprint.

In the operation stage, Strategy 4 shows a substantial decrease in environmental impact, reducing the single score by about 27% compared with the same stage in other scenarios. The results for the other strategies are relatively comparable across each life cycle stage. However, the inclusion of building-integrated photovoltaic (BIPV) systems in Strategy 4 increases the impact of the production stage by approximately 7% compared to the reference case, due to the additional materials and components required. To further reduce the total single score, it is recommended to combine several strategies. For example, integrating Strategies 2 and 4 could optimize the environmental footprint reduction by balancing material-related and operational improvements.

Implementation of Strategy 1 may be challenging, as most finishing materials are essential and cannot be easily eliminated. In such cases, selecting products with Environmental Product Declarations (EPDs) or lower embodied carbon values can be an effective approach. Prioritizing materials with verified low-carbon performance and applying minimalistic design principles could help achieve further environmental improvements within practical constraints.

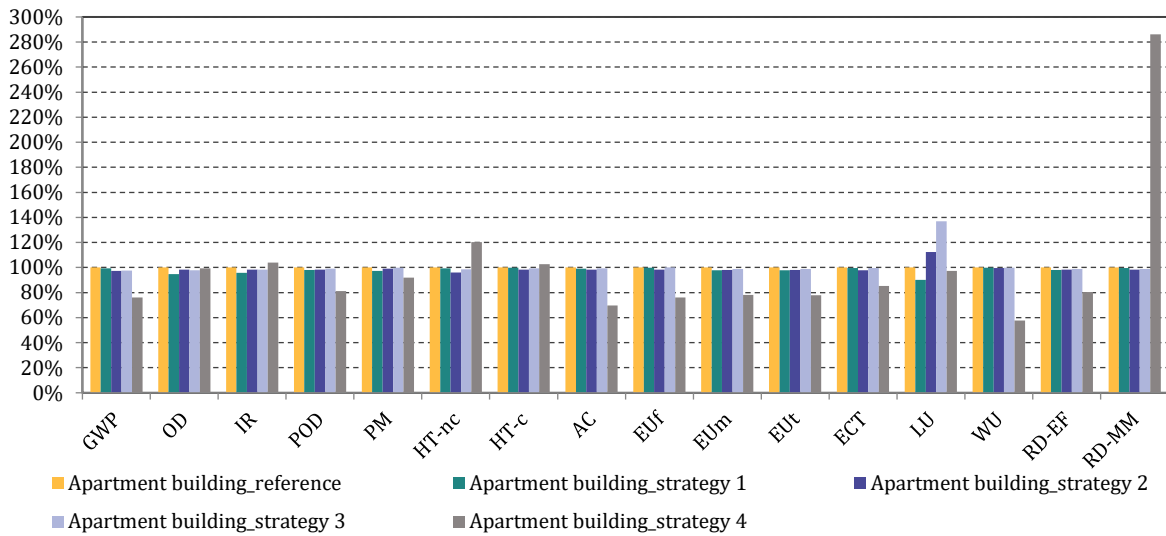


**Figure 6-10.** Comparison of environmental footprint results of all scenarios in different building life cycle.

Figure 6-11 illustrates a comparison of the LCIA results between the reference scenario and the four strategies across different environmental impact categories. Most of the studied strategies demonstrate reductions in several categories, specifically, 11 out of 16 impact indicators compared with the reference scenario. Overall, the scenarios do not show a significant reduction in all impact categories, except for Strategy 4, which exhibits a notable decrease in almost all categories. However, six categories namely IR, HT-nc, HT-c, EUf, LU, and RD-MM show increased impacts for certain strategies.

Strategy 4 presents higher impacts in IR, HT-nc, HT-c, and RD-MM categories. This increase is mainly due to the implementation of PV panels, which require high material inputs during production. The manufacturing of PV systems involves the extraction and processing of toxic and mineral-intensive materials such as solar glass, aluminium, polyester-complexed starch biopolymer, silicon, and copper, contributing to these impact categories. Specifically, Strategy 4 results in an increase of approximately 20% in HT-nc compared to the reference, primarily due to emissions from the production of semiconductor materials and other electronic components used in PV panels. Moreover, the 186% increase in RD-MM is attributed to the high demand for scarce metals and minerals used in PV module and inverter manufacturing. In contrast, the IR impact increases by only about 4%, reflecting the additional energy and radiation-related processes associated with PV component production, which remain relatively small compared to their operational benefits over the building's lifetime.

Strategies 2 and 3 show higher impacts in the LU category, with increases of approximately 12% and 37%, respectively, relative to the reference scenario. This increase is associated with the use of wooden components, such as timber walls and wood-framed windows. The greater land occupation and transformation linked to forestry activities and timber production processes explain this rise. Nevertheless, these strategies contribute positively to the overall carbon footprint reduction by promoting the use of renewable and low-carbon materials, which can be sustainably managed if sourced from certified forests.



**Figure 6-11.** Sixteen environmental impacts categories produced by the four studied scenarios.

### 6.3.6 Results of the combined scenario

Table 6-8 presents the results of the carbon footprint and environmental footprint across different building life cycle stages for both scenarios: the reference and the combined strategy. The carbon footprint corresponds to the climate change (GWP) impact, while the environmental footprint is expressed as the total single score aggregated from all assessed impact indicators.

**Table 6-8.** Carbon and environmental footprint in each phase of baseline and combined scenarios.

Life cycle stages	Reference		Combined strategy	
	Carbon footprint [kg CO <sub>2</sub> -eq/m <sup>2</sup> ]	Environmental footprint [mPt/m <sup>2</sup> ]	Carbon footprint [kg CO <sub>2</sub> -eq/m <sup>2</sup> ]	Environmental footprint [mPt/m <sup>2</sup> ]
Total	1.14E+03	112.8	7.93E+02	93.2
Production	3.68E+02	43.1	3.29E+02	41.8
Construction	5.36E+01	5.5	4.85E+01	5.1
Operation	7.01E+02	59.6	3.92E+02	42.6
End of life	2.21E+01	4.6	2.29E+01	3.8

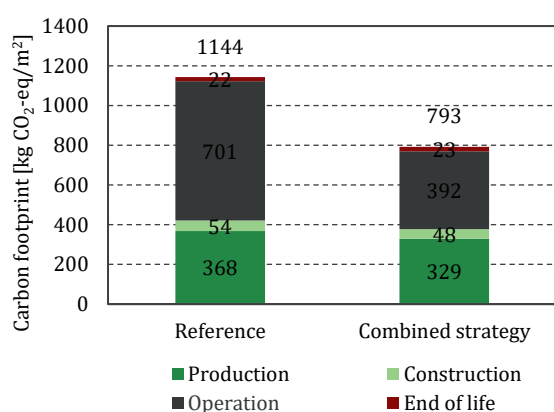
Figure 6-12 presents a comparison of the carbon footprint (kg CO<sub>2</sub>-eq/m<sup>2</sup>) between the reference scenario and the combined strategy across different building life cycle stages. The combination of the four studied strategies results in a reduction of the carbon footprint in all stages except for the end of life stage, as well as a lower total impact. The total carbon footprint is 793 kg CO<sub>2</sub>-eq/m<sup>2</sup>, representing a 31% decrease compared with the reference scenario. The major contributor to this overall reduction is the operation stage, primarily due to the integration of solar energy into the building's energy supply.

At the life cycle stage level, the impacts from production, construction, and operation are reduced by approximately 10%, 10%, and 44%, respectively, relative to the same stages in the reference

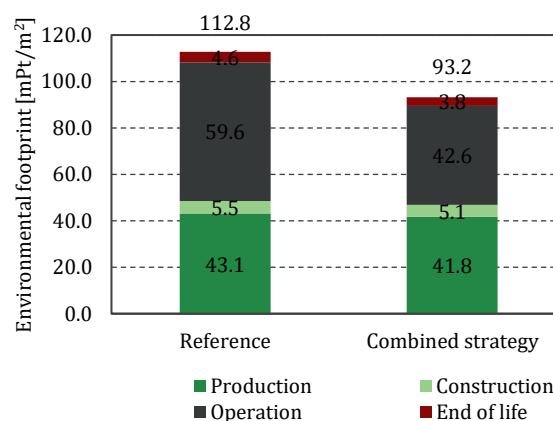
scenario. In contrast, the end of life stage shows a 3% increase in carbon footprint. This increase can be attributed to the inclusion of PV panel materials, which pose challenges for recycling and disposal at the end of the building's lifespan. Nevertheless, this impact is relatively small, representing only about 3% of the total carbon footprint.

Figure 6-13 shows the comparison of the environmental footprint (mPt) between the reference and combined scenarios for different life cycle stages. The combined strategy demonstrates a reduction in the total environmental footprint and across all stages. The total score of the combined strategy is 93.2 mPt/m<sup>2</sup>, corresponding to a decrease of 17% compared to the reference scenario. Again, the most significant improvement is observed in the operation stage, mainly due to reduced energy consumption and the contribution of on-site renewable energy generation.

When considering individual life cycle stages, the environmental footprint is reduced by 3%, 7%, 29%, and 18% in the production, construction, operation, and end of life stages, respectively, compared with the reference. Overall, the total single score derived from the sixteen impact categories indicates that the combined strategy has substantial potential for improving the building's environmental performance. Although some stages show relatively modest improvements, the operation stage provides a significant and decisive contribution to the overall reduction.



**Figure 6-12.** Carbon footprint results comparison based on the reference and combined scenarios.



**Figure 6-13.** Environmental footprint results comparison based on the reference and combined scenarios.

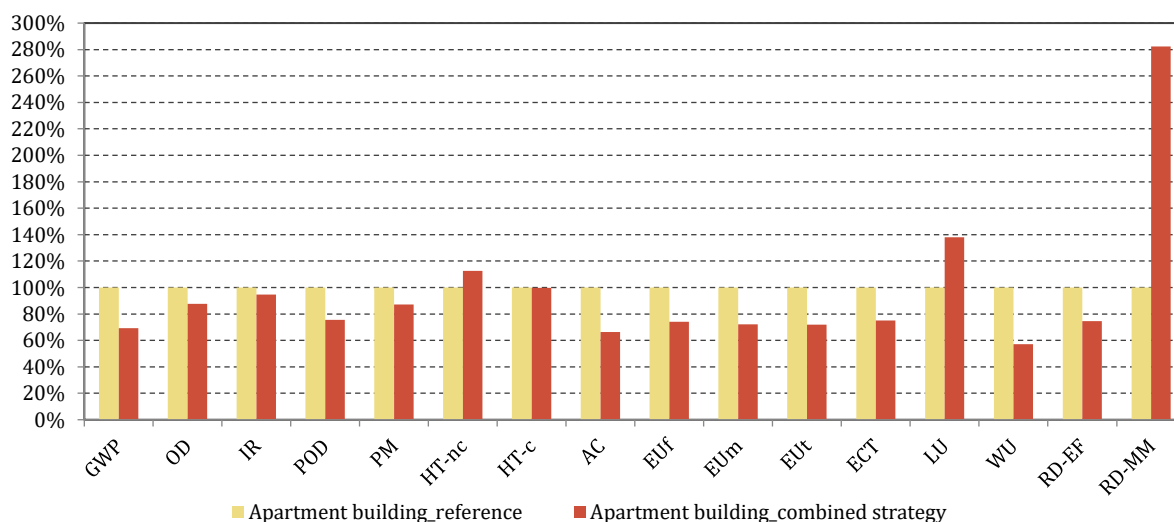
Figure 6-14 compares the environmental impact categories of the reference and combined scenarios. The combination of the four strategies demonstrates a significant potential to reduce impacts in almost all categories, except for HT-nc, HT-c, LU, and RD-MM. Remarkably, the combined scenario achieves reductions of 43%, 34%, and 32% for WU, AC, and GWP, respectively, compared to the reference. Additional notable reductions are observed in EUm, EUt, EUf, RD-EF, and POD, with decreases of approximately 29%, 29%, 26%, 26%, and 25%, respectively.

In contrast, the HT-nc, LU, and RD-MM impacts increase by approximately 12%, 38%, and 182%, respectively, compared to the reference scenario, while HT-c remains unchanged. The considerable increase in RD-MM impact is mainly attributed to Strategy 4, which involves the

installation of PV panels. This outcome aligns with the results shown in Figure 6-11, where PV integration substantially increases mineral and metal resource depletion due to the extraction and processing of rare and critical materials used in PV manufacturing.

The increase in LU impact is primarily associated with Strategies 2 and 3, which incorporate timber walls and wooden window frames. This rise reflects the higher land occupation and transformation linked to forestry activities. The increase in HT-nc impact is again mainly influenced by Strategy 4, due to emissions and toxic substances associated with PV panel production. However, as observed in Figure 6-11, although IR and HT-c impacts increase in Strategy 4 individually, these effects are mitigated when all strategies are combined, indicating that the integration of multiple design approaches can offset specific negative contributions.

Priority attention for future improvement of the combined strategy should focus on three categories: RD-MM, LU, and HT-nc. The RD-MM and HT-nc impacts could be mitigated through a more detailed analysis of PV panel materials, considering the use of low-embodied carbon or recycled alternatives to reduce reliance on raw and mineral-intensive resources. Future work should also address the resource sourcing, emission control, and end of life management of PV systems to minimize their life cycle impacts. For the LU impact, sustainable forestry practices and responsible timber sourcing should be prioritized, along with effective management of timber waste and disposal at the end of life stage.



**Figure 6-14.** Sixteen environmental impacts produced by the reference and combined scenarios.

### 6.3.7 Discussion on LCA of the apartment building in Cambodia and strategies

The selected building case study, a high-rise apartment building, is considered representative of high-rise residential buildings in Phnom Penh, the capital city of Cambodia. According to the survey conducted by Taing et al. (2023) with 85% of respondents being residents of Phnom Penh, common residential typologies of the city are identified: 23% of respondents lived in apartments (Taing et al., 2023). Long et al. (2024) reported that 38% of construction professionals including

engineers, architects, and urban planners believed that green affordable housing in Cambodia should adopt a high-rise typology (nine stories or more), and 25% suggested medium-rise buildings (four to eight stories) (Long et al., 2024). The preference for high-rise apartments is also driven by the high cost of urban land. Although the current number of high-rise residential buildings remains limited, the increasing urban population and demand for affordable housing suggest that this typology represents a promising prototype for future development. This rationale underpins the selection of this building as the case study for the LCA and for evaluating design strategies.

To analyze the environmental impacts of the building, the primary structural components: foundation, columns, beams, floors, staircases, walls, windows, doors, and finishing materials were disaggregated. One of the key challenges in conducting a building life cycle inventory (LCI) in Cambodia is the limited availability and accessibility of construction data. Permissions are often required for on-site surveys and measurements, while alternative data sources, such as bills of quantities (BoQs) and technical drawings, may exist in multiple versions, creating uncertainty about final material quantities. Consultation with engineers and construction staff was therefore essential to validate and supplement the missing information. As outlined in Section 6.1, all materials and quantities were derived from structural drawings and BoQs provided by the project architect. These datasets also constitute part of the results presented in this chapter. On-site investigation supported data validation and informed the identification of feasible design strategies to reduce impacts. This case study thus provides a benchmark LCI dataset for residential building LCAs in Cambodia. Future research can use this dataset not only for material inventories but also for understanding the layout and specifications of typical urban residential buildings.

The integration of Building Information Modelling (BIM) tools into LCA practice can further reduce uncertainty in both LCI and LCIA results, as BIM models capture detailed information on materials, geometry, and design changes (Feng, 2020). Linking BIM with LCA enables more accurate quantification of material flows, facilitates tracking of design revisions, and supports data-driven optimization for sustainable building design.

From the LCIA results, the environmental contributions of different life cycle stages and modules were identified. In most impact categories, the operation stage exhibits the highest share, primarily due to operational energy consumption (module B6). The production stage ranks second, with major contributions from raw material acquisition and manufacturing (modules A1 and A3). On average, the production, construction, operation, and end of life stages account for approximately 40%, 6%, 49%, and 5%, respectively, of the total impact across all categories. Therefore, building design strategies for high-rise apartments should prioritize reducing operational energy use and selecting low-impact materials to minimize total environmental burdens.

Analysis of individual building components and their materials further clarifies their relative influence across impact indicators. The results show that reinforcing steel is the largest contributor in almost all impact categories, followed by concrete, reflecting the dominance of

reinforced concrete structural systems. Although reducing these materials poses challenges, the use of green concrete and alternative reinforcement materials offers promising mitigation pathways. This component-level understanding helps designers identify critical materials and optimize designs accordingly.

In addition, ceramic tiles show relatively high contributions to particulate matter formation, comparable to concrete. This finding supports the feasibility of reducing ceramic tile use, as discussed in Long et al. (2025) (Long et al., 2025). Although their study found only a minor reduction (0.39%) in carbon emissions when removing ceramic tiles from external walls, combining this measure with other design strategies can enhance overall material efficiency. Moreover, substituting imported ceramic tiles with locally produced alternatives could help reduce embodied emissions and strengthen local manufacturing capacity. In this study, ceramic tiles accounted for about 2% of total building mass, higher than in Long et al. (2025), suggesting that similar interventions may yield greater reductions.

The LCIA results in this study include sixteen impact indicators from an environmental perspective. To facilitate comparison among design options, normalization and weighting were applied. These results, including characterized, normalized, and weighted values, are provided in Appendix D. The improvement achieved by the design strategies is expressed through the single score of environmental footprints. Among the four strategies, Strategy 4 achieved the largest reduction (approximately 12%) in total single score compared to the reference scenario, while Strategies 1 to 3 showed minimal or no improvement across most indicators. When the strategies were combined, the total environmental footprint decreased by 18%, as indicated by the single score. However, increases were observed in human toxicity (non-cancer effects), land use, and resource depletion (minerals and metals), reflecting trade-offs among the combined strategies. Such variations highlight the need for careful selection and optimization of interventions to balance benefits across impact categories. In terms of carbon footprint (GWP) alone, the reduction was 31%, establishing a valuable benchmark for studies focusing solely on life cycle carbon emissions.

Previous studies conducting cradle-to-grave LCAs on buildings have often focused solely on operational energy reduction rather than embodied carbon or materials-related impacts (Abd Rashid et al., 2017; Hasik et al., 2019; Iqbal et al., 2017; Tevis et al., 2019; Tulevech et al., 2018). The novelty of this study lies in integrating building design strategies with comprehensive LCA to address both operational and embodied impacts of a high-rise apartment building on a developing country. The proposed strategies contribute to the decarbonization of residential buildings and provide evidence-based insights for improving environmental performance.

This study acknowledges several limitations. The LCI inventory included only architectural and structural components, excluding MEP, and HVAC systems. Future studies should incorporate these systems to obtain a more complete representation of building impacts.

The operational energy data were derived from one year of electricity bills and assumed to remain constant over the 50-year building lifespan. Further research should monitor annual variations in

energy consumption to assess changes in efficiency over time. When materials or components are replaced in future scenarios, corresponding updates to energy consumption assumptions would also improve accuracy. Long-term monitoring would allow the relationship between material degradation and energy performance to be better understood.

Another limitation relates to the reliance on existing LCA databases, which may not fully reflect regional conditions. The absence of comprehensive Southeast Asian material and energy databases constrains local accuracy. Developing region-specific LCA databases should therefore be a research priority to support sustainable construction in developing contexts. Moreover, comparing results across different LCA software tools would provide insight into usability, data compatibility, and result sensitivity. Developing localized tools and interfaces could also make LCA more accessible to practitioners with limited technical expertise.

Although this study focused on a high-rise apartment building, the same framework can be applied to other residential typologies such as detached houses, shophouses or linked houses, and to non-residential high-rise buildings. Further research on Strategy 3, which involves timber structural walls, should evaluate material strength, durability, repair (B3), replacement (B4), and fire resistance to ensure structural feasibility and safety. Expanding the use of timber to additional building elements could further enhance environmental performance and support sustainable development if validated material data are available. Notably, several high-rise timber buildings have already been constructed in developed countries, including Mjosa Tower and Treet in Norway and Brock Commons Tallwood House in Canada (Bahrami et al., 2024).

Finally, future research should extend this framework to broader contexts and validate results through comparison with other published studies. A detailed comparative analysis will be presented in Chapter 8.

## 6.4 CHAPTER CONCLUSION

In this chapter, an LCA was conducted for an existing high-rise apartment building in Cambodia to evaluate four design strategies aimed at reducing environmental impacts. The reference building exhibits a carbon footprint (GWP) of 1144 kg CO<sub>2</sub>-eq/m<sup>2</sup> and an environmental footprint (single score) of 112.8 mPt/m<sup>2</sup>. The operation stage is identified as the largest contributor to the total impact, followed by the production stage. Within the production stage, the three components contributing most to environmental impacts are the structural systems, foundation piles, and finishing elements. The materials with the highest contributions are reinforcing steel, concrete, and ceramic tiles.

At the building level, strategies focused solely on minimizing material use, substituting materials with more eco-friendly alternatives, or introducing timber structural walls showed limited effectiveness in reducing overall environmental impacts. To achieve substantial improvement throughout the building's life cycle, it is essential to combine strategies that address both

embodied carbon from material use and operational carbon from energy consumption, while integrating renewable energy systems.

Among the tested strategies, the combined scenario proved to be the most effective. It resulted in a carbon footprint of 793 kg CO<sub>2</sub>-eq/m<sup>2</sup> and an environmental footprint of 93.2 mPt/m<sup>2</sup>, representing reductions of 31% and 18%, respectively, compared to the reference scenario.

This study successfully identified carbon emissions and environmental impacts at multiple levels: life cycle stages, information modules, building components, and materials. The findings provide a useful reference for future building LCA research in similar contexts, particularly in developing countries. Furthermore, the proposed simplified framework for conducting building LCAs offers a practical approach for designers and engineers to assess environmental impacts in a more accessible and feasible manner. This simplified method will be presented and compared across two building case studies in Chapter 7, focusing on a single impact indicator.

The assessment in this chapter considered the production, construction, operation, and end of life stages. For the end of life stage, waste processing (C3), it was assumed that all demolished materials are transported to landfill for disposal. This assumption highlights a limitation but also reflects the current waste management practices in Cambodia. Despite the challenges of applying a complete cradle-to-grave approach in such contexts, this study demonstrates the feasibility of conducting building LCAs in developing regions.

In the next chapter, a comparative analysis will be performed among three types of building LCAs: screening, simplified, and complete LCA, to evaluate their relative applicability and precision. For the complete LCA, the potential recyclability or waste processing of deconstruction materials will be considered; however, in the present case study, all materials are assumed to end their life at the landfill.

# 7

## Comparative life cycle assessment of two residential buildings

This chapter presents a comparative LCA of the two case studies: the townhouse and the apartment building, based on their LCIA results. In addition to comparing the results of all scenarios across the two residential building typologies in terms of life cycle stages, relevant impact categories, and environmental trade-offs, the core objective of this chapter is to conduct a comparative analysis of results obtained from three different LCA levels: screening, simplified, and complete LCA, across six environmental indicators. The LCA methodology is principally based on the EeBGuide framework, which defines the mandatory life cycle modules and building components to be considered for each LCA type. The variations between these LCA levels are discussed, and the acceptability and reliability of LCA simplification results are critically evaluated.

A part of this chapter was presented at the 6<sup>th</sup> International Conference on Building Energy and Environment (COBEE 2025), held at Eindhoven University of Technology, the Netherlands, from 06-10 July 2025, and was subsequently published in the book of conference proceedings.

*Long, M., Han, V., Leclercq, P., Reiter, S. (2025). Comparative life cycle carbon emission assessment of a residential building: a case study of Cambodia. COBEE 2025. The Book of Proceedings, p. 1-11. <https://hdl.handle.net/2268/335215>*

## 7.1 SIMPLIFICATION APPROACHES FOR THE LCA OF BUILDINGS

Introducing simplification approaches for building LCA to construction professionals, designers, and LCA practitioners is particularly beneficial for supporting decarbonization initiatives and promoting adoption within the Cambodian building sector. Given the almost non-existent application of building LCA in Cambodia, conducting studies that begin with small-scale residential buildings and gradually expand to high-rise or multi-family apartment buildings is advantageous. Such an approach can help establish benchmarks, even when tools and datasets are adopted from international or regional sources. Promoting building LCA practices contributes to reducing carbon emissions from the building sector and fosters the development of contextual life cycle inventory (LCI) data for construction materials, including national databases and emission factors, thereby improving the accuracy and regional relevance of future assessments.

LCA has increasingly been incorporated into the design phase of building projects (Budig et al., 2021; Dodd et al., 2017; Wittstock et al., 2012). These authors emphasize that evaluating design sustainability as early as possible is crucial and should be supported by user-friendly LCA methodologies. Simplification approaches in LCA may involve reducing the number of processes considered and limiting the system boundary to fewer life cycle stages. Such approaches are recommended in sustainability initiatives such as the European Commission's Joint Research Centre Level(s) framework and the EeBGuide (Dodd et al., 2017; Wittstock et al., 2012).

During the early design stages, quantifying and specifying building materials and products can be challenging, as final dimensions and technical details are often not yet finalized. However, these phases are critical for informed decision-making, and multiple design options are typically compared. Therefore, LCA methodologies applied during the design phase should not only be user-friendly but also time-efficient. In this context, simplified LCA approaches are particularly valuable. Hochschorner and Finnveden (2003) compared various simplified approaches and concluded that they are effective tools prior to conducting a complete and detailed LCA (Hochschorner & Finnveden, 2003).

The comparative LCA conducted in this study aims not only to provide benchmarks for similar research contexts and for the Cambodian building sector, but also to highlight key environmental impacts identified through the analysis of a townhouse and an apartment building. Furthermore, it evaluates the differences between simplified and complete LCA approaches, illustrating the potential ranges of variation in results. This comparison supports more accessible LCA practices while providing contextual references for future studies.

In the specific context of Cambodia, where LCA is not yet widely known or implemented in the building sector, this research seeks to introduce a reference framework based on three levels of LCA with varying degrees of detail. The initial focus is placed on residential buildings, which represent the most commonly constructed typology in urban areas. Establishing LCA practices for this typology can serve as a foundation before expanding research to other building types or infrastructure projects. Although the first implementation may not achieve full completeness, it

is essential to clearly define the specifications, methodological guidance, simplification procedures, and associated limitations. Transparent reporting of these aspects will support the gradual and structured integration of LCA into the Cambodian construction sector.

## 7.2 METHODOLOGY OF THE DIFFERENT LCA TYPES

In addition to comparing the LCA results of two residential building typologies, identifying the most relevant environmental impact categories, and analyzing trade-offs among impact categories, this chapter aims to evaluate the environmental performance of the case study buildings using three different LCA approaches: screening LCA, simplified LCA, and complete LCA. These approaches consider the production, construction, operation, and end of life stages; however, the included life cycle stages and system boundaries vary depending on the specific LCA type and its methodological requirements.

The comparative assessment applies these three LCA approaches to both reference buildings; the townhouse and the apartment building, as well as to five design strategies aimed at reducing environmental impacts. Detailed descriptions of the buildings are provided in Section 5.4 of Chapter 5 and Section 6.1 of Chapter 6, respectively. The building layouts and specifications are presented in Table 5-1 and Table 6-1. The townhouse typology examined in this study is commonly found in urban areas with high population density, while apartment buildings are prevalent in large cities, particularly in Phnom Penh, the capital of Cambodia. Therefore, these two case studies are representative of typical residential building typologies in the country. A summary of the strategies assessed for both buildings and their respective objectives is presented in Table 7-1.

**Table 7-1.** Studied scenarios and their descriptions for the townhouse and apartment building.

Townhouse	Apartment building
<b>Reference scenario: existing situation of the building case study</b>	
<b>Strategy 1: materials optimization and minimize decoration materials</b>	
<ul style="list-style-type: none"> <li>Remove finishing ceramic tiles from the several external walls</li> <li>Eliminate decorative steel frames from exterior windows and doors.</li> </ul>	<ul style="list-style-type: none"> <li>Remove natural stone from decorative and finishing elements that are used in living room and bathroom</li> </ul>
<b>Strategy 2: using environmental manufacturing and bio-based materials</b>	
<ul style="list-style-type: none"> <li>Replace normal reinforced concrete by lean concrete</li> <li>Replace aluminum window frames by wooden window frames</li> </ul>	<ul style="list-style-type: none"> <li>Replace the existing reinforced concrete using CEM II/A cement with the same density concrete using CEM II/B cement</li> </ul>
<b>Strategy 3: using lightweight timber structures</b>	
<ul style="list-style-type: none"> <li>Replace brick masonry walls by lightweight timber frames walls for the external walls</li> </ul>	<ul style="list-style-type: none"> <li>Replace the wall with a thickness of 200 mm, 150 mm, and 100 mm by timber walls</li> </ul>

<b>Strategy 4: utilizing renewable energy</b>	
<ul style="list-style-type: none"> <li>Implement solar PV panels on the existing roof (24 PV panels to be installed)</li> </ul>	<ul style="list-style-type: none"> <li>Install solar PV panels on the roof, west-oriented stair's envelope, and south-oriented rear balconies (352 PV panels to be installed)</li> </ul>
<b>Strategy 5: combined strategies</b>	

The study follows the same LCA methodological framework described in Chapters 5 and 6 and is conducted in accordance with the four main phases defined by ISO 14040 and ISO 14044: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The same LCA software and databases were used as in the previous chapters. The modelling and analysis were performed using SimaPro version 9.4.0.2. The ecoinvent 3 database was selected to model the life cycle inventory of the building units, accounting for inputs related to material production and energy consumption, as well as outputs to the technosphere throughout the building life cycle.

The life cycle impact assessment was conducted using the EF 3.0 method including 16 environmental indicators. The selected and relevant impact categories considered in this chapter are:

- 1) Climate change (GWP)
- 2) Particulate matter (PM)
- 3) Acidification (AC)
- 4) Water use (WU)
- 5) Resource use - fossils (RD-EF)

In addition to individual impact categories, the EF 3.0 method was also used to calculate the overall environmental performance of the buildings and their respective design strategies.

To enable a meaningful comparison among screening, simplified, and complete LCA approaches, the assessment includes multiple impact indicators rather than focusing solely on GWP. Long et al. (2025) suggest that comparative studies between screening and simplified LCA should evaluate several environmental impacts in order to examine deviations and assess the accuracy of screening results relative to more detailed approaches (Long et al., 2025). While a single indicator may be sufficient for specific objectives, a holistic assessment and hotspot analysis of building design options require multiple impact categories to avoid suboptimal solutions and burden shifting (Meex et al., 2018). Furthermore, according to the EeBGuide recommendations, comparisons with a complete LCA require a comprehensive set of indicators, as complete LCA typically includes multiple impact categories, whereas screening LCA may require only one or two (Wittstock et al., 2012).

The LCIA results were subsequently interpreted in accordance with the defined goal and scope of the study, enabling identification and analysis of differences among the results obtained from the three LCA approaches.

## 7.2.1 Mandatory building life cycle stages and modules

This section defines the system boundaries of the different LCA levels, focusing on the life cycle stages and modules considered in each approach over the entire building lifespan, as illustrated in Figure 7-1.

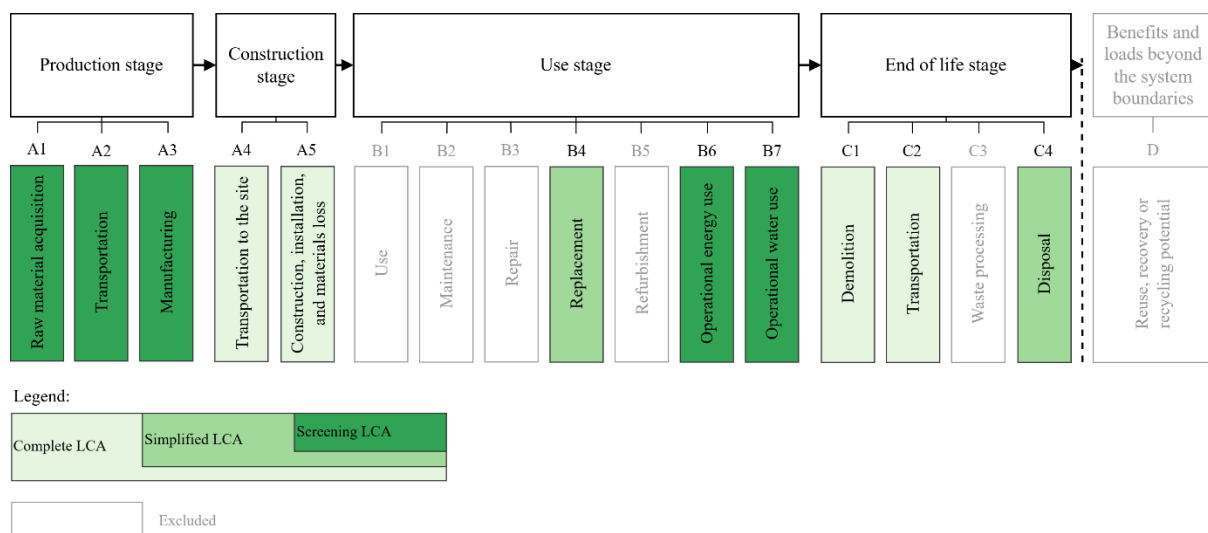
In this study, the screening LCA includes modules A1–A3 (production of building products and materials) and modules B6 (operational energy use) and B7 (operational water use) within the use stage.

The simplified LCA extends the system boundary of the screening LCA by additionally including module B4 (replacement of building products and materials) in the use stage and module C4 (disposal of demolition waste) in the end of life stage.

The complete LCA further expands the system boundary by incorporating modules A4 (transport of materials to the construction site) and A5 (construction and installation processes, including material losses) in the construction stage, as well as modules C1 (building demolition) and C2 (transport of demolition waste to landfill) in the end of life stage. These modules are added to those already included in the screening and simplified LCA approaches.

Modules B1–B3 (use, maintenance, and repair) and B5 (refurbishment) are excluded from all LCA levels due to the unavailability of reliable data and information for both case study buildings. Module C3 (waste processing) is also excluded because of insufficient context-specific data and supporting references to enable accurate modelling.

The LCI data for all included stages and modules are consistent with those previously presented in Chapter 5 for the townhouse case and Chapter 6 for the apartment building case.



**Figure 7-1.** Life cycle stages and modules to be considered for screening, simplified, and complete LCA based on EN 15978 standard (CEN, 2012b).

## 7.2.2 Mandatory building components

For the comparative assessment of the three LCA approaches; screening, simplified, and complete LCA, mandatory building components were defined based on the recommendations of the EeBGuide (Wittstock et al., 2012). The inclusion of building components varies according to the structural characteristics of each case study.

For example, the load-bearing structure of the townhouse consists of columns, beams, and staircases. In contrast, the apartment building includes additional structural elements, such as core walls for lift shafts and access ramps, in addition to the structural elements found in the townhouse. A comprehensive assessment of all relevant building components is required for the complete LCA, as summarized in Table 7-2.

Building services including heating, cooling, lighting, escalators/lifts, and water systems, are generally included in a complete LCA. However, these systems are excluded from the present study due to the absence of detailed and reliable data necessary to develop a bill of materials (BoM) for these services. As noted by Kjaer Zimmermann et al. (2019), even when simplification approaches are applied, building LCA remains a data-intensive process requiring detailed information on material quantities and product types (Kjaer Zimmermann et al., 2019). Furthermore, modelling in SimaPro requires precise input data for material quantities and specifications for each building component. In the present cases, the BoQ for building services including their quantities, material composition, dimensions, and technical specifications were unavailable.

The categorization and clarification of mandatory components are essential, as these components significantly influence impacts across multiple life cycle stages, particularly those related to material production and replacement. The classification adopted in this study is presented in Table 7-2.

**Table 7-2.** Summary of building components to be considered in different LCA level according to recommendations by EeBGuide.

	<b>Screening LCA</b>	<b>Simplified LCA</b>	<b>Complete LCA</b>
<b>Mandatory building components to be included</b>	<ul style="list-style-type: none"> <li>• Roof</li> <li>• Load-bearing structures</li> <li>• Building envelope including windows</li> <li>• Floor slabs</li> <li>• Foundation</li> <li>• Floor finishes/coverings</li> </ul>	<ul style="list-style-type: none"> <li>• Roof</li> <li>• Load-bearing structures</li> <li>• Building envelope including windows</li> <li>• Floor slabs</li> <li>• Foundation</li> <li>• Floor finishes/coverings</li> </ul>	<ul style="list-style-type: none"> <li>• Roof</li> <li>• Load-bearing structures</li> <li>• Building envelope including windows</li> <li>• Floor slabs</li> <li>• Foundation</li> <li>• Floor finishes/coverings</li> <li>• Wall finishes/coatings</li> </ul>

			• Doors
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## 7.3 RESULTS

This section presents a comparative analysis of the LCA results for the townhouse and the apartment building in Cambodia, highlighting the contribution of different life cycle stages to the overall environmental impacts using the complete LCA framework and the 16 environmental indicators of the EF 3.0 method. The LCIA results, including characterized, normalized, and weighted values for the townhouse analyzed in this chapter, are provided in Appendix B. To provide deeper insight into the results, the analysis identifies the most significant environmental impact categories based on the reference scenarios and four assessed design strategies. The effects and potential trade-offs of these strategies on the selected environmental indicators are examined for both residential building typologies.

Sub-section 7.3.4 further compares the environmental results derived from the three LCA approaches: screening LCA, simplified LCA, and complete LCA.

### 7.3.1 Impact assessment by life cycle stages of the townhouse and apartment building

Figure 7-2 illustrates the contribution of each life cycle stage to the characterized total environmental impact of the townhouse and the apartment building in Cambodia for each environmental indicator. The abbreviations of the environmental indicators follow those provided in Table 5-3 (Chapter 5). The system boundary applied in this chapter considers a cradle-to-grave approach, including production (A1–A3), construction (A4–A5), operation (B4, B6–B7), and end of life stages (C1–C2 and C4).

For the townhouse, the revised system boundary applied in this chapter differs from that used in Chapter 5; therefore, the reported results are not directly identical to those previously presented. To facilitate comparison of life cycle stage contributions, the total environmental impact for each indicator is normalized to 100%. The characterized results supporting the calculation of these percentage contributions are presented in Table 7-3.

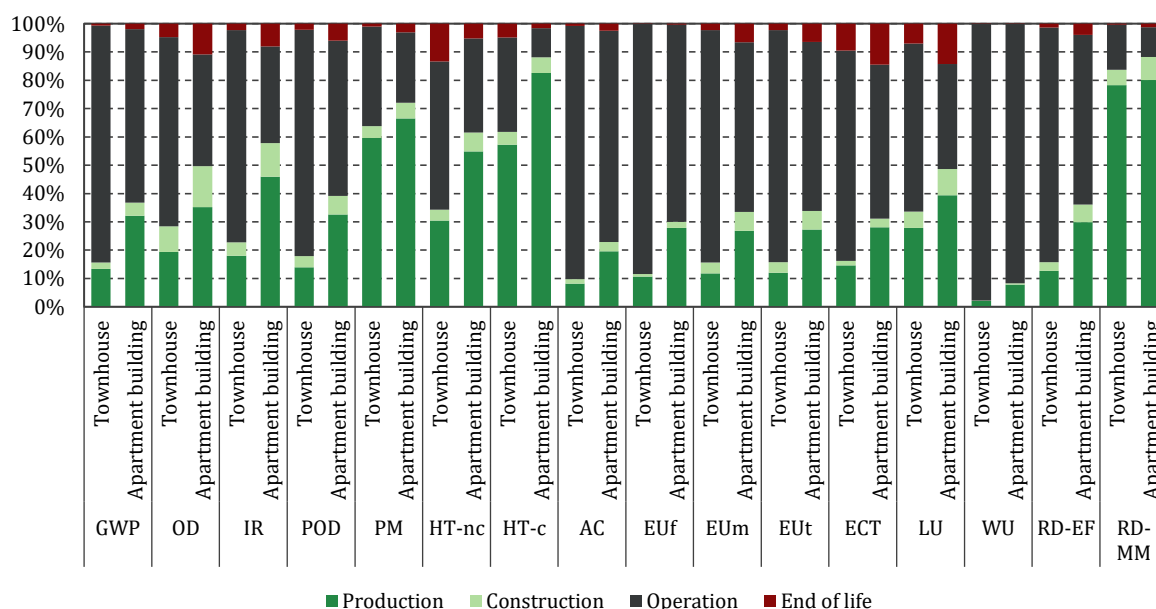
The characterized results indicate that the operation stage dominates most environmental impact categories in both buildings. Specifically, for 10 out of the 16 environmental indicators, the operation stage contributes more than 50% of the total impact. However, a distinction between the two buildings can be observed. For the townhouse, the operation stage is dominant in 13 indicators, whereas for the apartment building, its dominance is less pronounced.

Following the operation stage, the production stage is generally the second most influential life cycle stage. For the townhouse, production contributes more than 50% of the total impact in the categories of particulate matter (PM), human toxicity-cancer (HT-c), and resource use – minerals and metals (RD-MM), making it the dominant stage for these indicators. In contrast, for the apartment building, the production stage exceeds the contribution of the operation stage in six

impact categories: ionizing radiation (IR), PM, human toxicity non-cancer (HT-nc), HT-c, land use (LU), and RD-MM.

As summarized in Table 7-3, the townhouse, with a gross floor area (GFA) of 157 m<sup>2</sup> and a 50-year lifespan, generates 1344 kg CO<sub>2</sub>-eq/m<sup>2</sup>, corresponding to a total of 211 t CO<sub>2</sub>-eq over its lifetime. The apartment building, with a GFA of 3389 m<sup>2</sup>, generates 1144 kg CO<sub>2</sub>-eq/m<sup>2</sup>, corresponding to a total of 3877 t CO<sub>2</sub>-eq over the same lifespan. In both cases, the operation stage accounts for more than 50% of total greenhouse gas emissions, while the production stage contributes 13% and 32% of total GWP for the townhouse and apartment building, respectively.

In absolute terms, the total lifetime carbon emissions (GWP) of the townhouse correspond to approximately 5% of the total emissions of the apartment building over the 50-year lifespan. However, when expressed per square meter of GFA, the townhouse exhibits a higher carbon intensity than the apartment building.



**Figure 7-2.** Environmental impact contribution by each building life cycle stage of the townhouse and apartment building in different indicator.

**Table 7-3.** LCIA results from each life cycle stage in different impact categories of the townhouse and apartment building.

Impact category	Unit/m <sup>2</sup>	Townhouse					Apartment building				
		Production	Construction	Operation	End of life	Total	Production	Construction	Operation	End of life	Total
GWP	kg CO <sub>2</sub> eq	1.79E+02	3.08E+01	1.12E+03	9.80E+00	1.34E+03	3.68E+02	5.36E+01	7.01E+02	2.21E+01	1.14E+03
OD	kg CFC11 eq	1.20E-05	5.59E-06	4.12E-05	2.94E-06	6.17E-05	2.23E-05	9.16E-06	2.50E-05	6.89E-06	6.33E-05
IR	kBq U- <sup>235</sup> eq	6.60E+00	1.77E+00	2.75E+01	8.37E-01	3.67E+01	1.11E+01	2.87E+00	8.28E+00	1.94E+00	2.42E+01
POD	kg NMVOC eq	6.30E-01	1.75E-01	3.60E+00	9.95E-02	4.51E+00	1.34E+00	2.71E-01	2.26E+00	2.45E-01	4.11E+00
PM	disease inc.	1.02E-04	7.19E-06	5.99E-05	1.81E-06	1.71E-04	9.93E-05	8.26E-06	3.72E-05	4.50E-06	1.49E-04
HT-nc	CTUh	4.13E-06	5.18E-07	7.10E-06	1.80E-06	1.35E-05	6.77E-06	8.25E-07	4.10E-06	6.49E-07	1.23E-05
HT-c	CTUh	4.44E-07	3.53E-08	2.58E-07	3.81E-08	7.76E-07	1.15E-06	7.71E-08	1.43E-07	2.23E-08	1.39E-06
AC	mol H <sup>+</sup> eq	8.40E-01	1.70E-01	9.26E+00	8.07E-02	1.04E+01	1.53E+00	2.63E-01	5.83E+00	1.97E-01	7.82E+00
EUF	kg P eq	5.16E-03	4.32E-04	4.28E-02	5.93E-05	4.85E-02	1.06E-02	8.05E-04	2.65E-02	1.29E-04	3.80E-02
EUm	kg N eq	1.68E-01	5.47E-02	1.17E+00	3.25E-02	1.43E+00	3.30E-01	8.13E-02	7.38E-01	8.00E-02	1.23E+00
EUt	mol N eq	1.91E+00	6.06E-01	1.31E+01	3.55E-01	1.59E+01	3.73E+00	9.00E-01	8.18E+00	8.78E-01	1.37E+01
ECT	CTUe	4.43E+03	4.88E+02	2.26E+04	2.91E+03	3.04E+04	7.24E+03	7.89E+02	1.41E+04	3.74E+03	2.58E+04
LU	Pt	1.25E+03	2.63E+02	2.67E+03	3.13E+02	4.50E+03	1.79E+03	4.20E+02	1.68E+03	6.49E+02	4.54E+03
WU	m <sup>3</sup> depriv.	4.17E+01	3.15E+00	1.97E+03	6.00E-01	2.02E+03	8.16E+01	5.78E+00	9.61E+02	1.27E+00	1.05E+03
RD-E&F	MJ	1.74E+03	4.17E+02	1.13E+04	1.94E+02	1.37E+04	3.37E+03	7.00E+02	6.75E+03	4.50E+02	1.13E+04
RD-MM	kg Sb eq	5.05E-03	3.48E-04	1.03E-03	2.08E-05	6.44E-03	2.85E-03	2.91E-04	3.71E-04	4.60E-05	3.56E-03

### 7.3.2 Impact assessment of most relevant impact categories in different scenarios

The calculation of the total environmental impact, expressed as a single score (millipoints), for both buildings and all assessed strategies aim to identify the most relevant environmental impact categories contributing to the overall performance. The single score calculation was previously conducted for the townhouse in Section 5.5.3 (Chapter 5) and for the apartment building in Section 6.2.3 (Chapter 6). However, it should be noted that the life cycle stages included for the townhouse in Chapter 5 were limited, whereas in the present chapter a more complete system boundary is applied. Therefore, this section verifies whether the previously identified relevant impact categories remain consistent under the expanded system boundary or whether differences emerge.

The identification of relevant impact categories is supported by the LCA results of both buildings. In addition, this section evaluates the changes, trade-offs, and improvement potentials of the assessed strategies across the identified impact categories.

Figure 7-3 and Figure 7-5 present the normalized and weighted results for the townhouse and the apartment building, respectively, using the normalization and weighting factors provided in Table 5-4. The total environmental impacts of the reference townhouse and apartment building amount to 140.6 mPt/m<sup>2</sup> and 112.8 mPt/m<sup>2</sup>, corresponding to 22 points and 382 points in absolute terms, respectively (see Table 7-4 and Table 7-5). The adopted approach prioritizes the analysis of environmental impacts at the characterization level, followed by normalization and weighting to support hotspot identification across the most relevant indicators.

The most relevant impact categories for both buildings, identified according to the EF 3.0 method, are summarized in Table 7-4 and Table 7-5, while the remaining categories are grouped under “Others.” In accordance with the Product Environmental Footprint Category Rules (PEFCR), toxicity-related indicators are excluded from hotspot analysis and benchmarking and are instead reported separately (EC, 2017).

The most relevant impact categories (ranked from highest to lowest contribution) are:

- Townhouse: GWP, PM, RD-EF, WU, and AC
- Apartment building: GWP, PM, RD-EF, AC, and WU

Overall, the same five impact categories are identified as most relevant for both building typologies. However, their ranking differs slightly. For the townhouse, water use (WU) ranks fourth and acidification (AC) fifth, whereas for the apartment building these two categories switch positions, with AC ranked fourth and WU fifth. This difference is largely attributable to the apartment building’s larger scale (15 stories), for which the production stage contributes 19–31% to AC impact compared with only 7–14% in the townhouse. The apartment building’s total material mass and mass-to-floor-area ratio are approximately 49 and 2.3 times higher than those of the townhouse, increasing production-stage contributions across indicators and influencing hotspot ranking. Among these five categories, four are predominantly influenced by the operation

stage (largely due to electricity consumption), while particulate matter (PM) is mainly driven by the production stage, as observed consistently across the five assessed scenarios (Figure 7-3 and Figure 7-5).

When examining changes and trade-offs among the relevant impact categories for the townhouse, Strategy 4 demonstrates the highest improvement potential. Compared to the reference scenario, Strategy 4 achieves reductions of approximately 29% in RD-EF, 33% in GWP, 33% in WU, and 37% in AC (Figure 7-4). In contrast, Strategy 2 results in a 1% increase in total life cycle impact relative to the reference scenario, while the other strategies achieve moderate reductions ranging from 11% to 13%.

For the apartment building, Strategy 4 similarly provides the most significant environmental improvement, reducing impacts by approximately 8% (PM), 20% (RD-EF), 24% (GWP), 30% (AC), and 42% (WU) compared to the reference case (Figure 7-6). The remaining strategies show limited or negligible reductions across the most relevant impact categories. These findings suggest that strategies targeting operational energy and water efficiency are particularly effective, while strategies focusing solely on material substitution require further development to achieve substantial improvements in the identified hotspot categories.

The results presented in Figure 7-4 and Figure 7-6 are based on characterized results and total life cycle impacts for the relevant impact categories, as detailed in Table 7-4 and Table 7-5 for the townhouse and apartment building, respectively. All characterized results and environmental impact scores are expressed per square meter of GFA, ensuring comparability between the two building typologies.

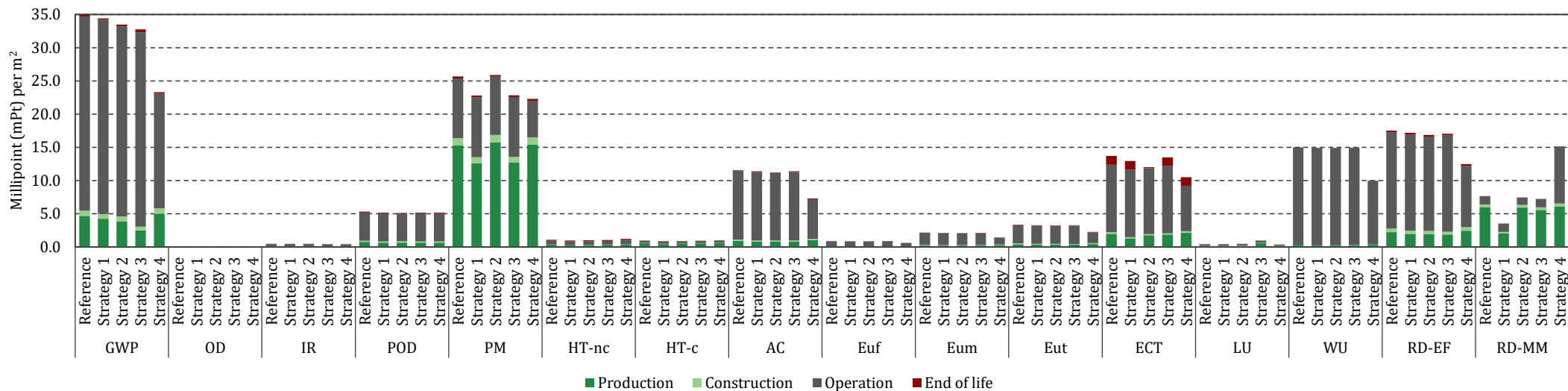


Figure 7-3. The normalized and weighted life cycle impacts of the townhouse as per different scenarios.

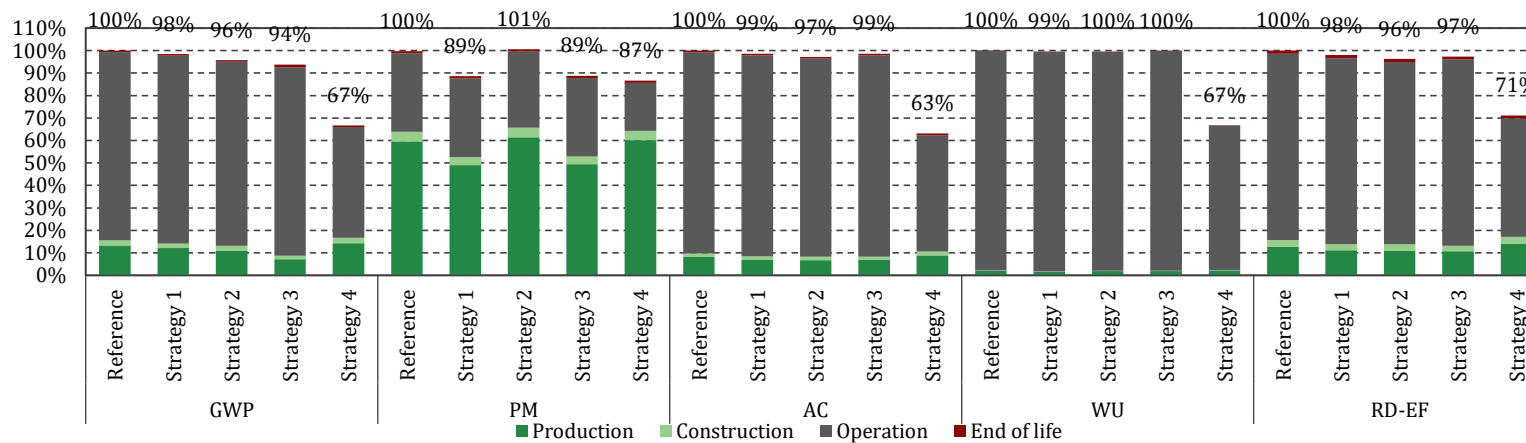


Figure 7-4. The characterized life cycle impacts of the townhouse as per different scenarios across the relevant impact categories.

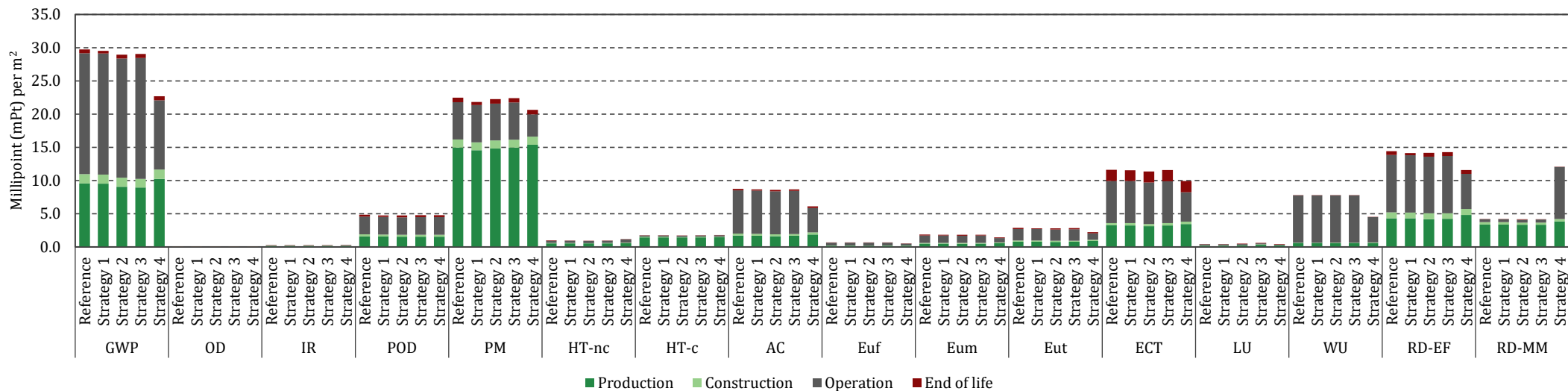


Figure 7-5. The normalized and weighted life cycle impacts of the apartment building across different scenarios.

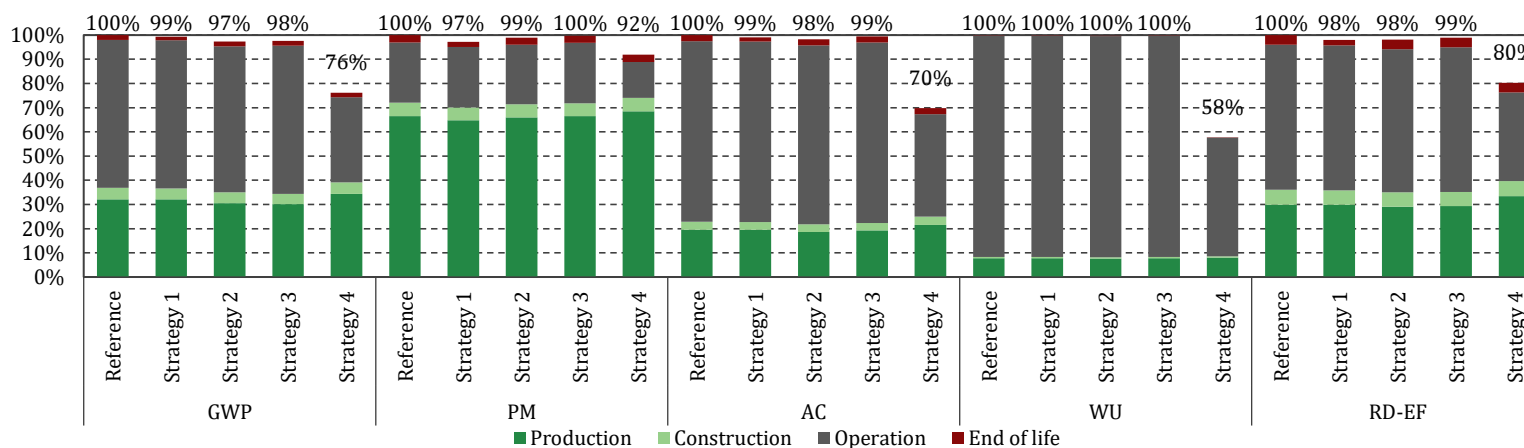


Figure 7-6. The characterized life cycle impacts of the apartment building as per different scenarios across the relevant impact categories.

**Table 7-4.** Characterized results and total life cycle impacts of the relevant impact categories and other impacts in different scenarios for the townhouse.

<b>Townhouse</b>					
<b>GWP (kg CO<sub>2</sub>-eq/m<sup>2</sup>)</b>					
<b>Life cycle/Scenario</b>	<b>Reference</b>	<b>Strategy 1</b>	<b>Strategy 2</b>	<b>Strategy 3</b>	<b>Strategy 4</b>
Production	179	163	147	96	192
Construction	31	28	29	22	32
Operation	1124	1124	1101	1124	663
End of life	10	9	9	18	10
Total	1344	1323	1287	1260	897
Total score per impact (mPt/m <sup>2</sup> )	35.0	34.4	33.5	32.8	23.3
<b>PM (disease inc./m<sup>2</sup>)</b>					
Production	1.02E-04	8.36E-05	1.05E-04	8.42E-05	1.02E-04
Construction	7.19E-06	6.17E-06	7.32E-06	5.90E-06	7.26E-06
Operation	5.99E-05	5.99E-05	5.83E-05	5.99E-05	3.65E-05
End of life	1.81E-06	1.77E-06	1.69E-06	1.75E-06	1.79E-06
Total	1.71E-04	1.51E-04	1.72E-04	1.52E-04	1.48E-04
Total score per impact (mPt/m <sup>2</sup> )	35.0	34.4	33.5	32.8	23.3
<b>AC (mol H<sup>+</sup> eq/m<sup>2</sup>)</b>					
Production	0.84	0.72	0.69	0.73	0.92
Construction	0.17	0.16	0.16	0.14	0.18
Operation	9.26	9.25	9.12	9.26	5.35
End of life	0.08	0.08	0.08	0.08	0.08
Total	10.35	10.21	10.06	10.20	6.53
Total score per impact (mPt/m <sup>2</sup> )	11.6	11.4	11.2	11.4	7.3
<b>WU (m<sup>3</sup> depriv./m<sup>2</sup>)</b>					
Production	42	32	37	39	44
Construction	3	3	3	3	3
Operation	1971	1970	1966	1971	1296
End of life	1	1	1	1	1
Total	2016	2006	2006	2013	1344
Total score per impact (mPt/m <sup>2</sup> )	15.0	14.9	14.9	14.9	10.0
<b>RD-EF (MJ)</b>					
Production	1740	1530	1490	1462	1908
Construction	417	372	399	339	429
Operation	11338	11329	11106	11338	7213
End of life	194	189	182	182	191

Total	13689	13421	13177	13321	9741
Total score per impact (mPt/m <sup>2</sup> )	17.5	17.2	16.9	17.0	12.5
<b>Other impacts (OD, IR, POD, HT-nc, HT-c, Euf, Eum, Eut, ECT, LU, and RD-MM)</b>					
Total score of other impacts (mPt/m <sup>2</sup> )	70.9	30.6	33.5	35.5	36.6
<b>Total environmental impact (mPt/m<sup>2</sup>)</b>	140.6	131.2	135.9	134.5	112.0

**Table 7-5.** Characterized results and total life cycle impacts of the relevant impact categories and other impacts in different scenarios for the apartment building.

<b>Apartment building</b>					
<b>GWP (kg CO<sub>2</sub>-eq/m<sup>2</sup>)</b>					
<b>Life cycle/Scenario</b>	<b>Reference</b>	<b>Strategy 1</b>	<b>Strategy 2</b>	<b>Strategy 3</b>	<b>Strategy 4</b>
Production	368	367	349	344	393
Construction	54	52	51	49	54
Operation	701	701	690	701	402
End of life	22	16	22	23	22
Total	1144	1136	1113	1117	872
Total score per impact (mPt/m <sup>2</sup> )	29.8	29.5	28.9	29.0	22.7
<b>PM (disease inc./m<sup>2</sup>)</b>					
Production	9.93E-05	9.67E-05	9.85E-05	9.93E-05	1.02E-04
Construction	8.26E-06	8.01E-06	8.10E-06	7.94E-06	8.31E-06
Operation	3.72E-05	3.72E-05	3.67E-05	3.72E-05	2.22E-05
End of life	4.50E-06	3.17E-06	4.50E-06	4.46E-06	4.50E-06
Total	1.49E-04	1.45E-04	1.48E-04	1.49E-04	1.37E-04
Total score per impact (mPt/m <sup>2</sup> )	22.5	21.8	22.2	22.4	20.6
<b>AC (mol H+ eq/m<sup>2</sup>)</b>					
Production	1.53	1.52	1.46	1.51	1.69
Construction	0.26	0.26	0.25	0.24	0.26
Operation	5.83	5.83	5.79	5.83	3.31
End of life	0.20	0.14	0.20	0.20	0.20
Total	7.82	7.75	7.69	7.78	5.46
Total score per impact (mPt/m <sup>2</sup> )	8.7	8.6	8.6	8.7	6.1
<b>WU (m<sup>3</sup> depriv./m<sup>2</sup>)</b>					
Production	82	81	79	81	84
Construction	6	6	6	6	6
Operation	961	961	959	961	515
End of life	1	1	1	1	1

Total	1049	1048	1046	1049	606
Total score per impact (mPt/m <sup>2</sup> )	7.8	7.8	7.8	7.8	4.5
<b>RD-EF (MJ/m<sup>2</sup>)</b>					
Production	3370	3359	3269	3308	3761
Construction	700	682	677	649	705
Operation	6745	6745	6665	6745	4132
End of life	450	252	450	443	451
Total	11266	11038	11062	11145	9049
Total score per impact (mPt/m <sup>2</sup> )	14.4	14.1	14.2	14.3	11.6
<b>Other impacts (OD, IR, POD, HT-nc, HT-c, Euf, Eum, Eut, ECT, LU, and RD-MM)</b>					
Total score of other impacts (mPt/m <sup>2</sup> )	29.6	29.3	29.1	29.5	33.9
<b>Total environmental impact (mPt/m<sup>2</sup>)</b>	<b>112.8</b>	<b>111.2</b>	<b>110.8</b>	<b>111.7</b>	<b>99.4</b>

### 7.3.3 Comparison of LCA results of trade-off impact categories across all scenarios

Figure 7-7 presents a focused comparison of the LCA results for environmental impact categories that exhibit notable increases and trade-offs across the assessed strategies for both residential building typologies. These impact categories are disaggregated by life cycle stage to better understand their driving mechanisms. The selected trade-off categories were identified based on their substantial increases relative to the reference scenario, as previously presented in Figure 5-13 (townhouse) and Figure 6-11 (apartment building).

The identified trade-off indicators are:

- Townhouse:  
PM, HT-nc, HT-c, LU, and RD-MM  
(or PM, LU, and RD-MM when toxicity indicators are excluded)
- Apartment building:  
IR, HT-nc, HT-c, Euf, LU, and RD-MM  
(or IR, Euf, LU, and RD-MM when toxicity indicators are excluded)

Among these, land use (LU) and resource use – minerals and metals (RD-MM) show the most significant escalation across strategies.

For the townhouse, LU and RD-MM impacts increase to nearly twice the reference values in several scenarios. In the case of the apartment building, RD-MM increases up to three times the reference value. For the townhouse, LU impact rises notably when strategies involving wooden materials are implemented (Strategies 2 and 3). Under Strategy 3, LU increases by approximately 117% compared to the reference scenario. When all strategies are combined (Strategy 5), this

increase is slightly reduced to 109%, representing an 8% improvement compared to Strategy 3 alone. This substantial increase is primarily driven by the production stage, where the contribution shifts from 32% in the reference scenario to 141% in Strategy 3, more than a fourfold increase.

For the apartment building, LU increases by 12% and 37% under Strategy 2 (wooden window frames) and Strategy 3 (timber walls), respectively, compared to the reference scenario. When all strategies are combined, LU increases by an additional 1%, unlike the townhouse case where the combined strategy slightly mitigates the increase. Similar to the townhouse, the production stage is the dominant contributor to LU escalation.

Regarding RD-MM impact, Strategy 4 results in a 98% increase relative to the reference townhouse. When all strategies are combined (Strategy 5), this increase decreases slightly to 87% above the reference. The main contributor to this trade-off is the operation stage under Strategy 4, where its share of the total RD-MM impact rises from 16% in the reference scenario to 112%.

A similar trend is observed for the apartment building. Under Strategy 4, the operation stage contribution to RD-MM increases from 10% in the reference case to 185%, leading to an overall RD-MM increase of 186% compared to the reference. When all strategies are combined, the total RD-MM impact slightly decreases to 182%, yet remains substantially higher than the baseline.

Other trade-off impacts are observed in individual strategies; however, most of them do not persist when all strategies are combined (Strategy 5), with the exception of HT-nc, LU, and RD-MM. When toxicity indicators are considered, particular attention should be given to HT-nc, especially for the apartment building, where module B6 (operational energy use) significantly drives the increase.

In contrast, LU is mainly influenced by modules A1 and A3 (raw material supply and manufacturing) within the production stage, while RD-MM is primarily driven by module B6 (operational energy use) in both building cases. These findings highlight the importance of examining burden shifting between life cycle stages and impact categories when implementing environmental improvement strategies.

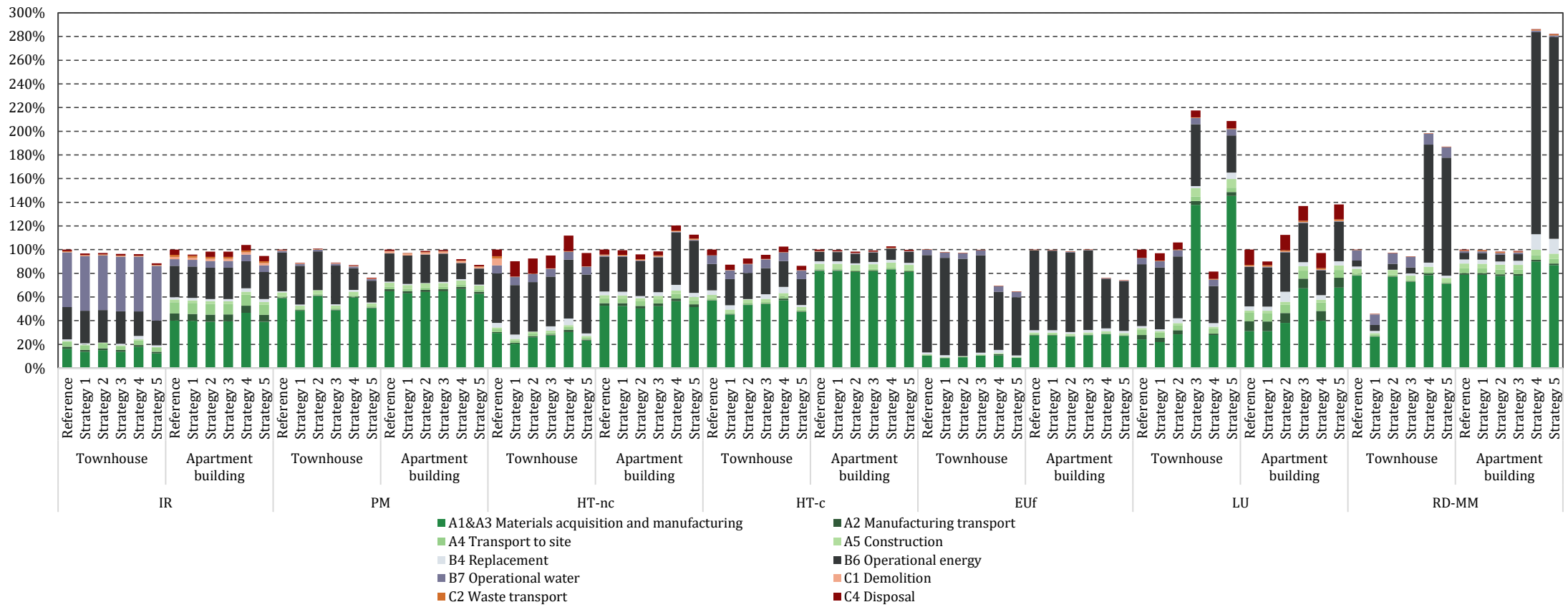


Figure 7-7. LCA results comparison of trade-off environmental impact categories for all scenarios.

### 7.3.4 Comparison of screening, simplified, and complete LCA results across relevant impact categories and the total environmental footprint

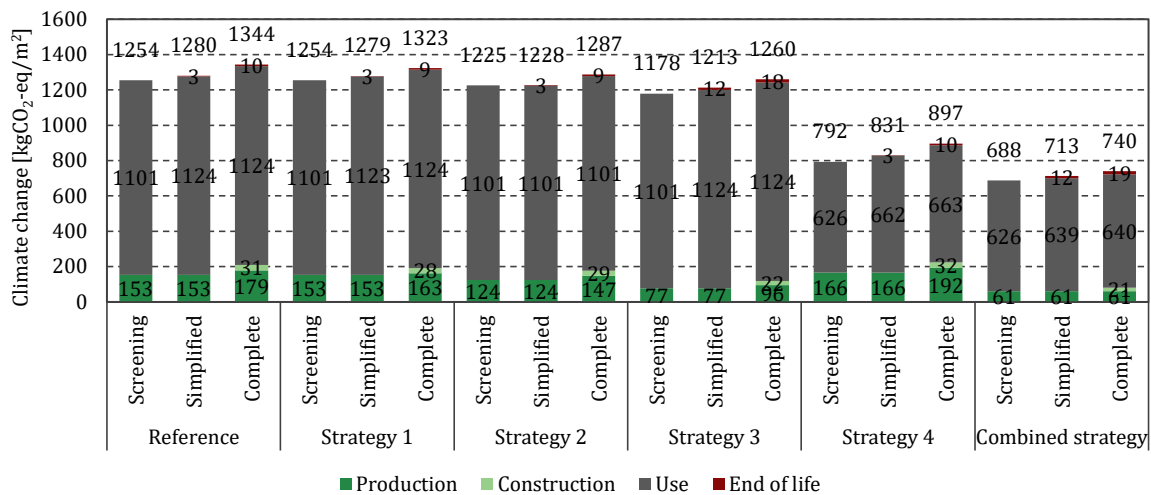
Comparisons of life cycle impact results calculated using three LCA approaches; screening, simplified, and complete, were conducted for both building cases. The analysis considered only the most relevant environmental impact indicators identified in the previous subsection: climate change (GWP), particulate matter (PM), acidification (AC), water use (WU), and fossil resource use (RD-EF), as these indicators contribute significantly to the total life-cycle environmental impact.

#### 1) Climate change (GWP) impact

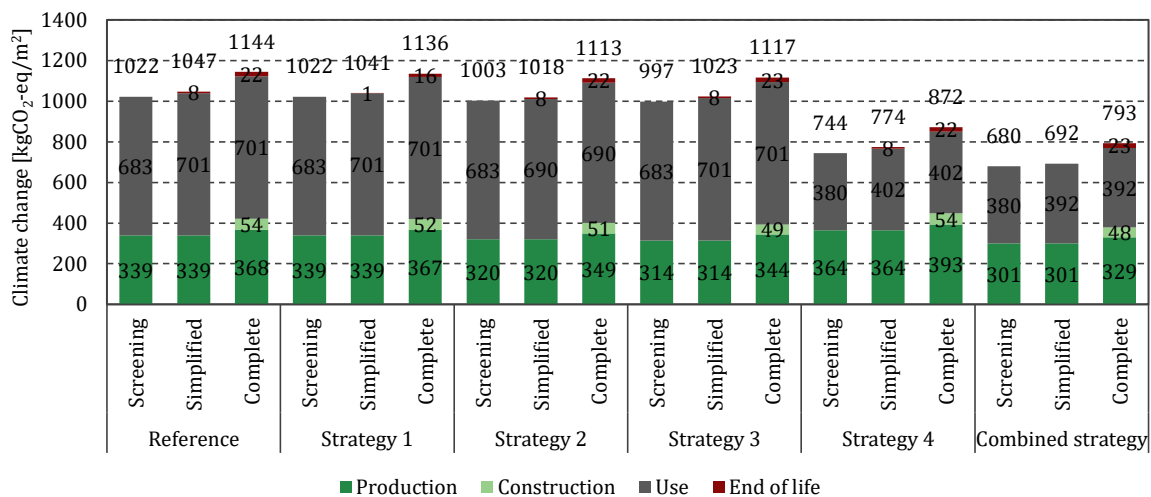
Figure 7-8 and Figure 7-9 present comparisons of total GWP results for the reference and five studied scenarios calculated using the three LCA approaches. For the townhouse, the reference scenario showed total GWP values of 1254, 1280, and 1344 kg CO<sub>2</sub>-eq/m<sup>2</sup> for the screening, simplified, and complete LCA, respectively. The screening and simplified LCA results differ from the complete LCA result by 7% and 5%, respectively.

Across the five strategies (Strategies 1–4 and the combined strategy), screening LCA results differ from complete LCA results by 5%, 5%, 7%, 12%, and 7%, respectively. Strategy 4 shows the largest discrepancy between screening and complete LCA results. For the same strategies, simplified LCA results differ from complete LCA results by 3%, 5%, 4%, 7%, and 4%, respectively. Overall, for the townhouse, differences between screening and complete LCA results across all scenarios range from 5% to 12%, while differences between simplified and complete LCA results range from 3% to 7%.

For the apartment building, the reference scenario shows total GWP values of 1022, 1047, and 1144 kg CO<sub>2</sub>-eq/m<sup>2</sup> for screening, simplified, and complete LCA, respectively. These correspond to differences of 11% and 8% for screening and simplified LCA relative to complete LCA. For screening LCA, results for Strategies 1–4 and the combined strategy differ from complete LCA results by 10%, 10%, 11%, 15%, and 14%, respectively. Simplified LCA results for the same strategies differ from complete LCA results by 8%, 9%, 8%, 11%, and 13%, respectively. Thus, across all scenarios including the reference case, discrepancies relative to complete LCA range from 10% to 15% for screening LCA and from 8% to 13% for simplified LCA.



**Figure 7-8.** Climate change (GWP) impact results comparison across different types of LCA and scenarios of the townhouse.



**Figure 7-9.** Climate change (GWP) impact results comparison across different types of LCA and scenarios of the apartment building.

## 2) Particulate matter (PM) impact

Figure 7-10 and Figure 7-11 present a comparison of particulate matter (PM) impact results for the reference scenario and the five assessed strategies, calculated using the three LCA approaches.

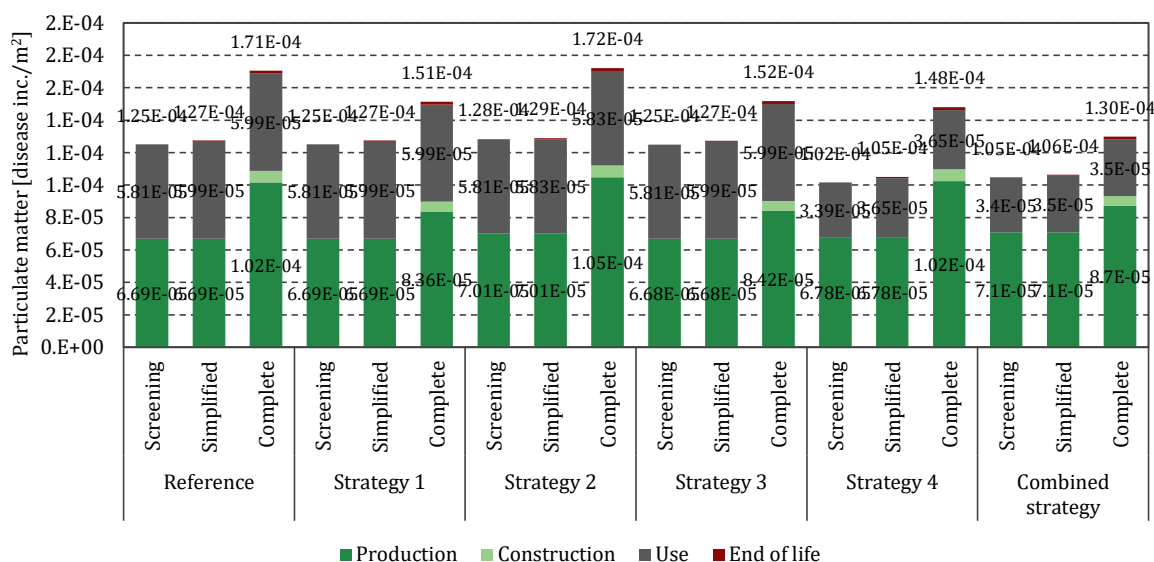
For the townhouse, the reference scenario shows total PM impacts of  $1.25E-04$ ,  $1.27E-04$ , and  $1.71E-04$  disease incidences/ $m^2$  for the screening, simplified, and complete LCA, respectively. The screening and simplified LCA results differ from the complete LCA result by 27% and 25%, respectively (Figure 7-10).

Across the five strategies (Strategies 1–4 and the combined strategy), screening LCA results differ from complete LCA results by 17%, 25%, 18%, 31%, and 19%, respectively. For the same

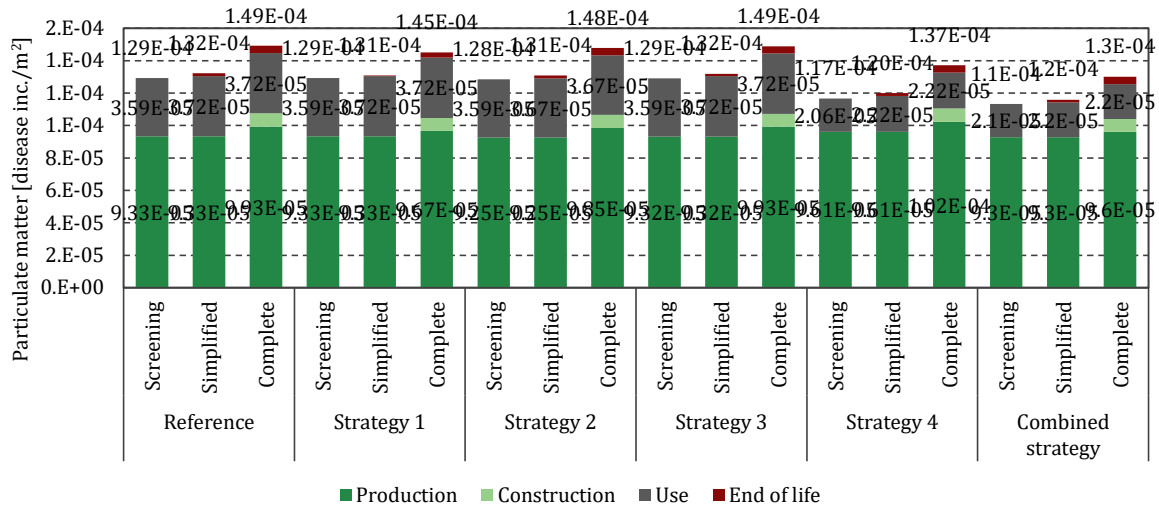
strategies, simplified LCA results differ from complete LCA results by 16%, 25%, 16%, 29%, and 18%, respectively. Overall, for the townhouse case, differences between screening and complete LCA results across all scenarios (including the reference scenario) range from 17% to 31%, while differences between simplified and complete LCA results range from 16% to 29%.

For the apartment building, as presented in Figure 7-11, the reference scenario shows total PM impacts of 1.29E-04, 1.32E-04, and 1.49E-04 disease incidences/m<sup>2</sup> for the screening, simplified, and complete LCA, respectively. These correspond to differences of 13% and 11% for screening and simplified LCA relative to complete LCA.

For the screening LCA, results for Strategies 1–4 and the combined strategy differ from complete LCA results by 11%, 13%, 13%, 15%, and 13%, respectively. Simplified LCA results for the same strategies differ from complete LCA results by 10%, 11%, 11%, 13%, and 11%, respectively. Overall, for the apartment building, differences relative to complete LCA across all scenarios range from 11% to 15% for screening LCA and from 10% to 13% for simplified LCA.



**Figure 7-10.** Particulate matter (PM) impact results comparison across different types of LCA and scenarios of the townhouse.



**Figure 7-11.** Particulate matter (PM) impact results comparison across different types of LCA and scenarios of the apartment building.

### 3) Acidification (AC) impact

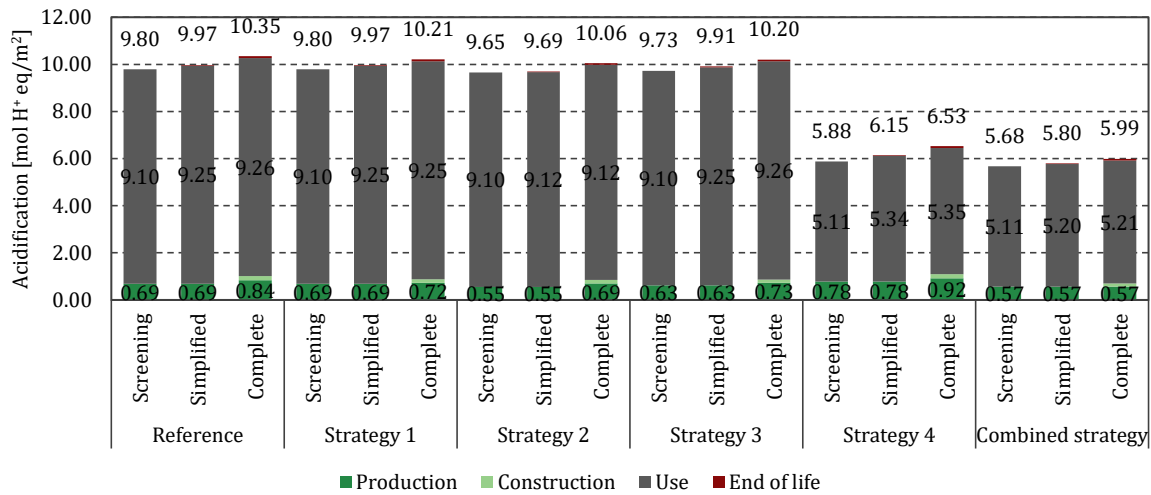
Figure 7-12 and Figure 7-13 present the total life-cycle acidification (AC) impact results for the townhouse and apartment building, respectively, comparing all assessed scenarios calculated using the three LCA approaches: screening, simplified, and complete.

For the existing townhouse, the AC impact is 9.80, 9.97, and 10.35 mol H<sup>+</sup> eq/m<sup>2</sup> for the screening, simplified, and complete LCA, respectively (Figure 7-12). The screening and simplified LCA results differ from the complete LCA result by 5% and 4%, respectively.

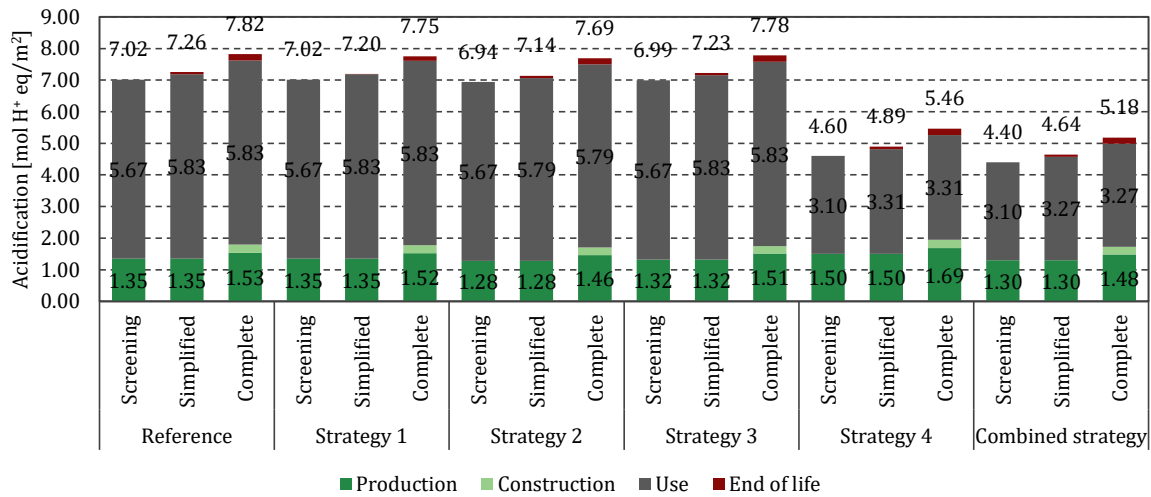
Across the five strategies (Strategies 1–4 and the combined strategy), differences between screening and complete LCA results are 4%, 4%, 5%, 10%, and 5%, respectively. For simplified LCA, the differences relative to complete LCA are 2%, 4%, 3%, 6%, and 3%, respectively. Overall, for the townhouse, discrepancies between screening and complete LCA range from 4% to 10%, while discrepancies between simplified and complete LCA range from 2% to 6%.

For the existing apartment building, the AC impact is 7.02, 7.26, and 7.82 mol H<sup>+</sup> eq/m<sup>2</sup> for screening, simplified, and complete LCA, respectively (Figure 7-13). These correspond to differences of 10% and 7% for screening and simplified LCA relative to complete LCA.

Across Strategies 1–4 and the combined strategy, screening LCA results differ from complete LCA results by 9%, 10%, 10%, 16%, and 15%, respectively. Simplified LCA results differ from complete LCA results by 7%, 7%, 7%, 10%, and 10%, respectively. Overall, across all scenarios including the reference case, differences relative to complete LCA range from 9% to 16% for screening LCA and from 7% to 10% for simplified LCA.



**Figure 7-12.** Acidification (AC) impact results comparison across different types of LCA and scenarios of the townhouse.



**Figure 7-13.** Acidification (AC) impact results comparison across different types of LCA and scenarios of the apartment building.

#### 4) Water use (WU) impact

Figure 7-14 and Figure 7-15 present the total life-cycle water use (WU) impact results for the townhouse and apartment building, respectively, comparing all scenarios calculated using screening, simplified, and complete LCA.

For the existing townhouse, WU impacts are 1999, 2005, and 2016 m<sup>3</sup> depriv./m<sup>2</sup> for screening, simplified, and complete LCA, respectively (Figure 7-14). The differences between screening and complete LCA and between simplified and complete LCA are both approximately 1%.

Across the five strategies, screening LCA results differ from complete LCA results by approximately 1% in all cases, except for Strategy 1, which shows a difference of only 0.31%.

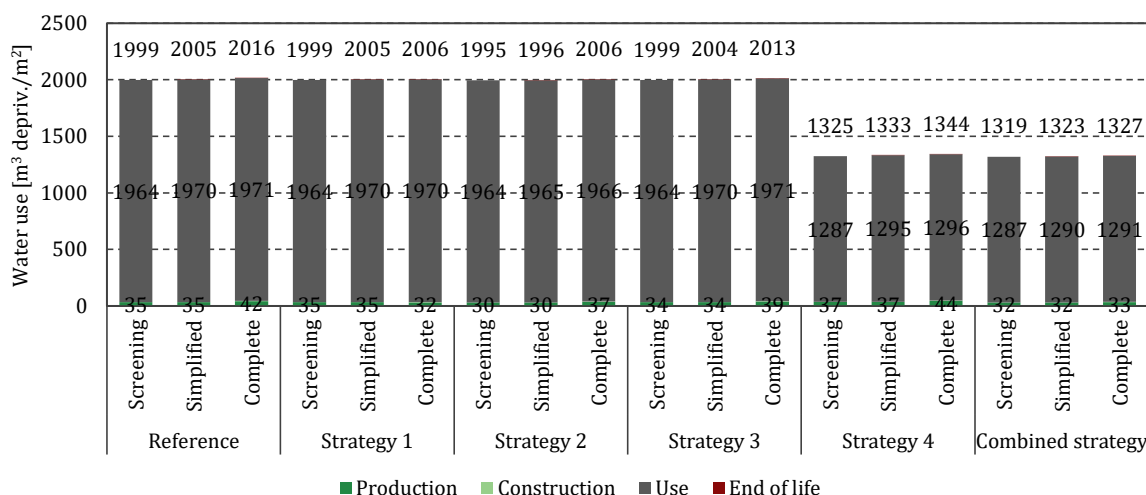
Simplified LCA results differ from complete LCA results by 0.04%, 1%, 0.42%, 1%, and 0.36% for Strategies 1–4 and the combined strategy, respectively.

Overall, for the townhouse, results from screening and simplified LCA are very close to those of complete LCA, with differences generally around or below 1%.

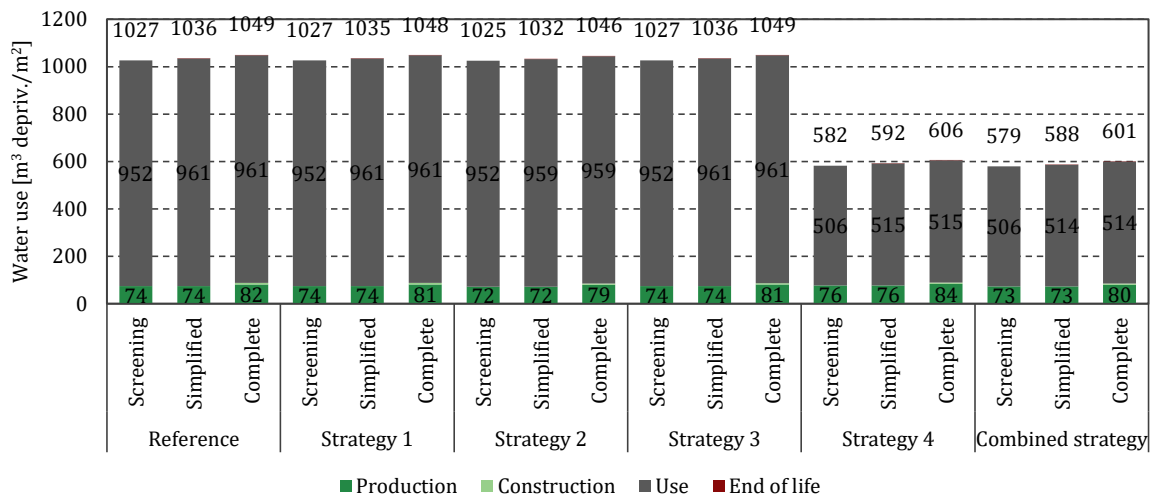
For the existing apartment building, WU impacts are 1027, 1036, and 1049 m<sup>3</sup> depriv./m<sup>2</sup> for screening, simplified, and complete LCA, respectively (Figure 7-15). These correspond to differences of 2% and 1% for screening and simplified LCA relative to complete LCA.

Across Strategies 1–3, differences between screening and complete LCA are 2%, while differences between simplified and complete LCA are 1%. For Strategy 4 and the combined strategy, differences are 4% (screening) and 2% (simplified), respectively. Overall, relative to complete LCA, discrepancies range from 2% to 4% for screening LCA and from 1% to 2% for simplified LCA.

The WU life-cycle impact results calculated using the three LCA approaches for both residential buildings show only minor differences, indicating strong comparability among methodologies for this impact category.



**Figure 7-14.** Water use (WU) impact results comparison across different types of LCA and scenarios of the townhouse.



**Figure 7-15.** Water use (WU) impact results comparison across different types of LCA and scenarios of the apartment building.

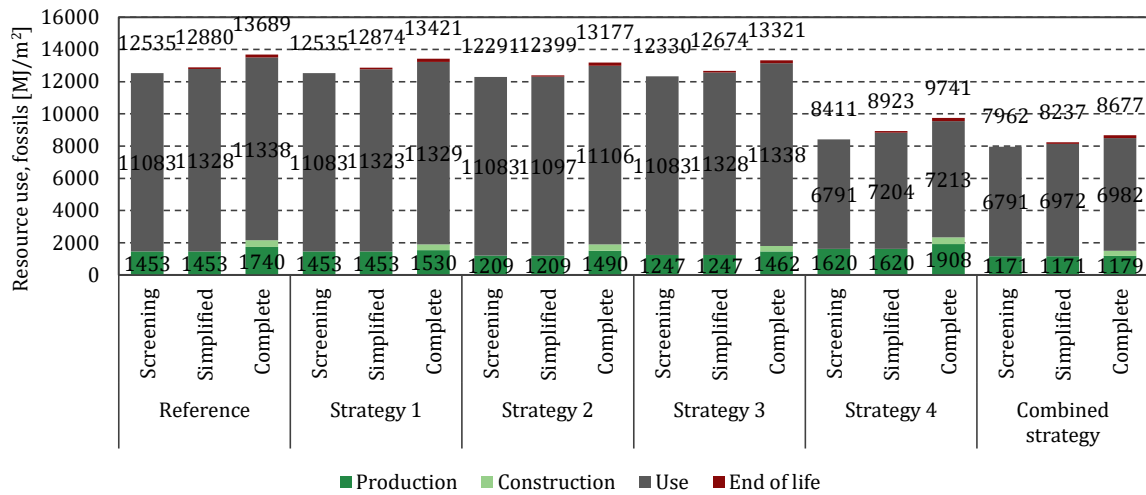
### 5) Resource use, fossils (RD-EF) impact

For the townhouse reference scenario, fossil resource use (RD-EF) is 12,535, 12,880, and 13,689 MJ/m<sup>2</sup> for screening, simplified, and complete LCA, respectively (Figure 7-16). The screening and simplified LCA results differ from the complete LCA result by 8% and 6%, respectively.

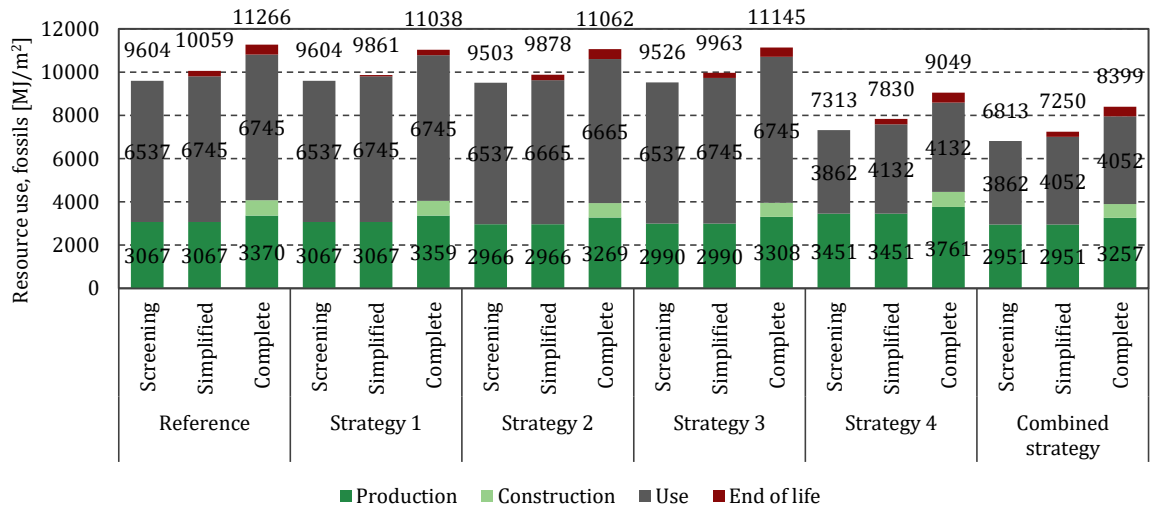
Across the five strategies, differences between screening and complete LCA results are 7%, 7%, 7%, 14%, and 8% for Strategies 1–4 and the combined strategy, respectively. Differences between simplified and complete LCA results are 4%, 6%, 5%, 8%, and 5%, respectively. Overall, for the townhouse, discrepancies between screening and complete LCA range from 7% to 14%, while those between simplified and complete LCA range from 4% to 8%.

For the apartment building (Figure 7-17), RD-EF impacts are 9,604, 10,059, and 11,266 MJ/m<sup>2</sup> for screening, simplified, and complete LCA, respectively. The reference scenario shows differences of 15% (screening) and 11% (simplified) relative to complete LCA.

Across Strategies 1–4 and the combined strategy, screening LCA results differ from complete LCA results by 13%, 14%, 15%, 19%, and 19%, respectively. Simplified LCA results differ from complete LCA results by 11%, 11%, 11%, 13%, and 14%, respectively. Overall, discrepancies range from 13% to 19% for screening LCA and from 11% to 14% for simplified LCA.



**Figure 7-16.** Resource use, fossils (RD-EF) impact results comparison across different types of LCA and scenarios of the townhouse.



**Figure 7-17.** Resource use, fossils (RD-EF) impact results comparison across different types of LCA and scenarios of the apartment building.

## 6) Total environmental impact (single score)

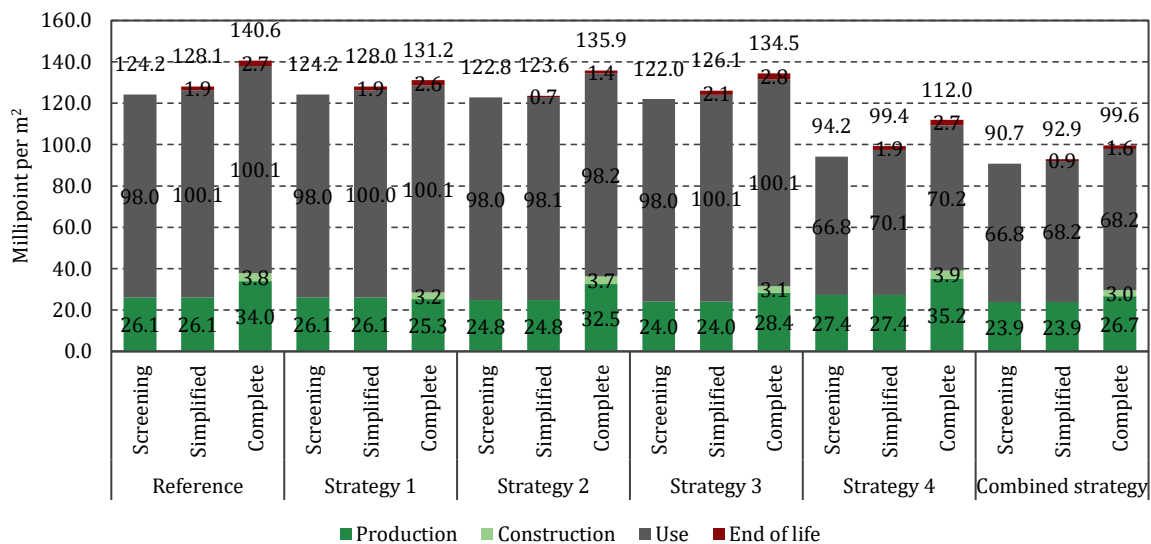
Figure 7-18 and Figure 7-19 illustrate the total environmental impact single scores calculated using the screening, simplified, and complete LCA methodologies for each scenario in the townhouse and apartment building, respectively.

Figure 7-18 shows that the total environmental impact score of the townhouse is 124.2, 128.1, and 140.6 millipoints per  $m^2$  (mPt/ $m^2$ ) for the screening, simplified, and complete LCA, respectively. These results correspond to differences of 12% and 9% for screening and simplified LCA relative to complete LCA.

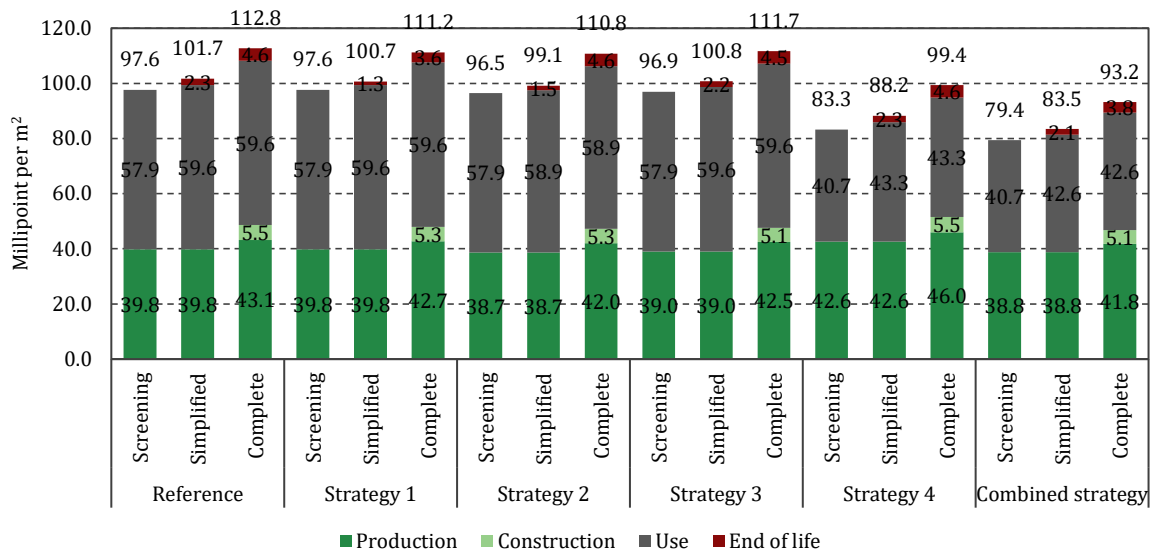
Across Strategies 1–4 and the combined strategy, differences between screening and complete LCA results are 5%, 10%, 9%, 16%, and 9%, respectively. For the same strategies, differences between simplified and complete LCA results are 2%, 9%, 6%, 11%, and 7%, respectively. Overall, for the townhouse, discrepancies between screening and complete LCA range from 5% to 16%, while those between simplified and complete LCA range from 2% to 11%.

Figure 7-19 presents the total environmental impact single scores for the apartment building calculated using the three LCA approaches. For the reference scenario, total impacts are 97.6, 101.7, and 112.8 mPt/m<sup>2</sup> for screening, simplified, and complete LCA, respectively. These correspond to differences of 13% and 10% for screening and simplified LCA relative to complete LCA.

Across Strategies 1–4 and the combined strategy, screening LCA results differ from complete LCA results by 12%, 13%, 13%, 16%, and 15%, respectively. Simplified LCA results differ from complete LCA results by 9%, 11%, 10%, 11%, and 10%, respectively. Overall, relative to complete LCA, total environmental impact scores range from 12% to 16% for screening LCA and from 9% to 11% for simplified LCA.



**Figure 7-18.** The normalized and weighted life cycle impacts of the townhouse as per scenario.



**Figure 7-19.** The normalized and weighted life cycle impacts of the apartment building as per scenario.

### 7.3.5 Summary of screening, simplified, and complete LCA results comparison

Based on the results presented in Figures 7-8 to 7-19, Figure 7-20 and Figure 7-21 summarize the ranges of differences between screening and complete LCA results and between simplified and complete LCA results across the relevant impact categories and total environmental impacts for both buildings.

On average, screening LCA results compared with complete LCA results for GWP show differences of 7% for the townhouse (Figure 7-20a) and 12% for the apartment building (Figure 7-21c). For PM, AC, WU, and RD-EF impacts, the differences for the townhouse and apartment building are 23% and 13%, 6% and 12%, 1% and 3%, and 9% and 16%, respectively. For total environmental impact, the differences are 10% for the townhouse and 14% for the apartment building. Overall, considering multiple impact indicators and scenarios, the differences between screening and complete LCA results are generally higher for the apartment building than for the townhouse, except for the PM indicator.

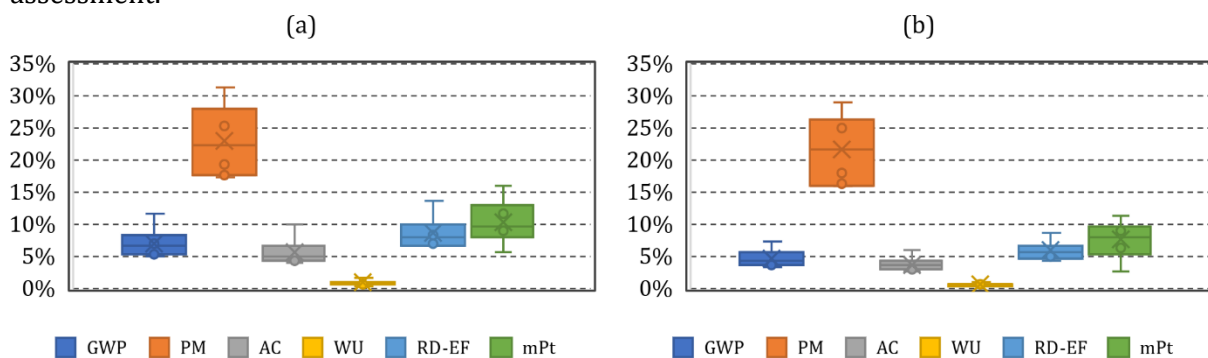
A similar pattern is observed for comparisons between simplified and complete LCA results. The average differences for each indicator show that the apartment building generally exhibits larger deviations than the townhouse, again with the exception of PM. Across the same set of indicators (from GWP to total environmental impact expressed in mPt; Figure 7-20b and Figure 7-21d), the differences for the townhouse and apartment building are 5% and 10%, 22% and 11%, 4% and 8%, 0.45% and 2%, 6% and 12%, and 7% and 10%, respectively.

Overall, when comparing both screening and simplified LCA results with complete LCA results, the apartment building shows larger deviations than the townhouse across all relevant indicators except PM, for which the townhouse exhibits higher differences. This may be attributed to the broader range and larger quantities of construction materials included in the complete LCA of the

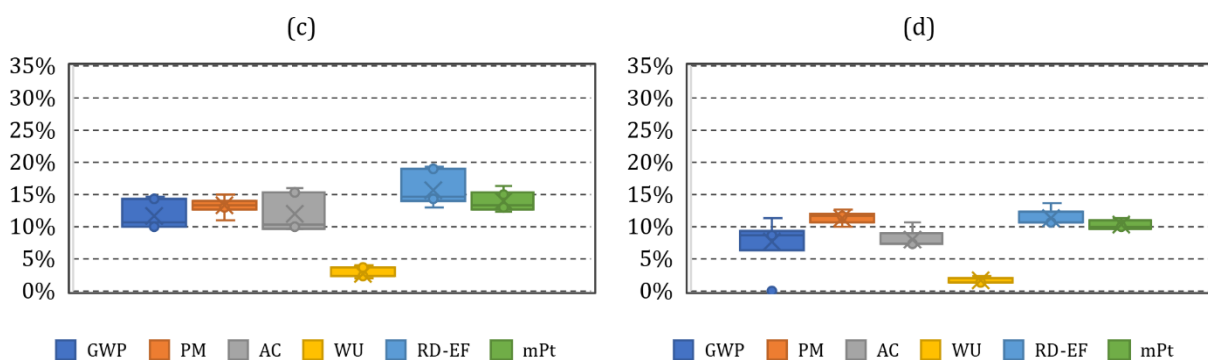
apartment building compared with the townhouse. In contrast, mandatory building components included in the complete LCA of the townhouse are limited to internal walls, external wall finishes/coatings, external stairs, doors, and other finishing or covering materials, which may reduce variability.

Across all assessed impact indicators for both buildings, PM and RD-EF show the largest discrepancies between simplified or screening approaches and complete LCA. For the townhouse and apartment building, respectively, the highest differences reach 23% and 16% for screening LCA, and 22% and 12% for simplified LCA.

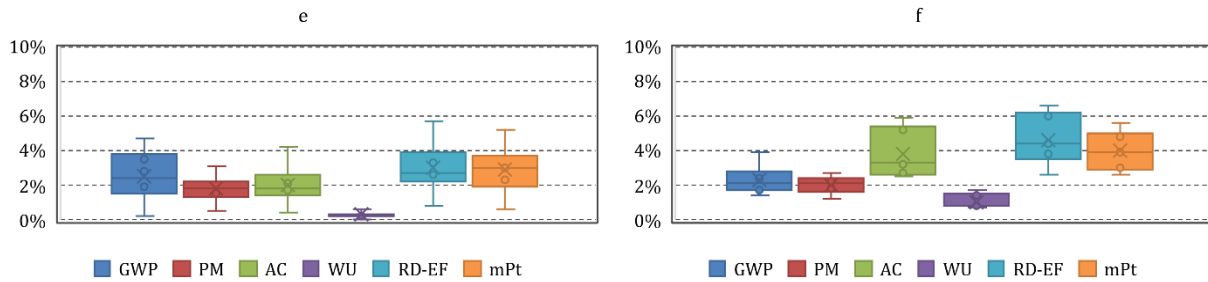
Finally, when comparing screening and simplified LCA results directly across all indicators for both buildings (Figure 7-22), the differences between these two approaches do not exceed 6% for the townhouse, with an average difference of 2% (Figure 7-22e), and do not exceed 7% for the apartment building, with an average difference of 3% (Figure 7-22f). These findings indicate that screening and simplified LCA methods produce broadly comparable results for building life-cycle assessment.



**Figure 7-20.** Percentage difference of screening vs. complete LCA (a) and simplified vs. complete LCA (b) results of the townhouse.



**Figure 7-21.** Percentage difference of screening vs. complete LCA (c) and simplified vs. complete LCA (d) results of the apartment building.



**Figure 7-22.** Difference in percentage of screening vs. simplified of the townhouse (e) and apartment building (f).

This section further investigates screening, simplified, and complete LCA approaches by evaluating the environmental impacts associated with each building life cycle stage, as well as the most relevant impact categories for the two studied typologies. It also examines the resulting hierarchy of the assessed strategies.

Table 7-6 presents the percentage contribution of each life cycle stage to both GWP and total environmental impact for the two case studies. For the townhouse, the contribution of the production stage to GWP is consistent across screening, simplified, and complete LCA, ranging between 23–24% of the total life cycle impact. In contrast, the operation stage shows a lower contribution in the complete LCA (69%) compared to screening and simplified approaches (76% and 74%, respectively). A similar trend is observed for total environmental impact: while production stage contributions remain comparable across all LCA types, the operation stage contribution from the complete LCA (84%) is slightly lower than those from the simplified and screening LCAs (87% and 88%, respectively). For the apartment building, the production stage contribution to GWP is also consistent across all LCA approaches (32–33%). However, the operation stage contribution from the complete LCA (61%) is again lower than that of the screening and simplified LCAs (67%). When considering total environmental impact (aggregating all sixteen impact categories), the production stage contributions from simplified and complete LCA are similar (39% and 38%, respectively), while the screening LCA shows a slightly higher share (41%). For the operation stage, screening and simplified LCA yield identical results (59%), whereas the complete LCA again shows a lower contribution (53%).

Overall, these results indicate that production stage contributions to GWP are consistent across LCA methodologies, whereas operation stage contributions tend to be slightly lower in the complete LCA compared to the screening and simplified approaches. This pattern is also observed for total environmental impact in both case studies, with the exception of the townhouse production stage, where the complete LCA shows a marginally higher contribution.

Table 7-7 presents the contribution and cumulative ranking of the most relevant impact categories identified for both case studies across the three LCA methodologies. The results show consistent ranking of impact categories across screening, simplified, and complete LCA, aligning with the findings in Section 7.3.2. Additionally, the cumulative contribution of the five most relevant impact categories is highest in the complete LCA, followed by the simplified LCA, and lowest in the screening LCA.

**Table 7-6.** Environmental impacts of life cycle stages for the townhouse and apartment building, calculated using screening, simplified, and complete LCA approaches.

Townhouse												
Environmental indicator	Screening LCA				Simplified LCA				Complete LCA			
	Prod.	Con.	Oper.	EoL	Prod.	Con.	Oper.	EoL	Prod.	Con.	Oper.	EoL
GWP	12%		88%		12%		87%	0.3%	13%	2%	84%	1%
Total env. impact	21%		79%		20.4%		78%	1.5%	24%	3%	71%	2%
Apartment building												
Environmental indicator	Screening LCA				Simplified LCA				Complete LCA			
	Prod.	Con.	Oper.	EoL	Prod.	Con.	Oper.	EoL	Prod.	Con.	Oper.	EoL
GWP	33%		67%		32%		67%	1%	32%	5%	61%	2%
Total env. impact	41%		59%		39%		59%	2%	38%	5%	53%	4%

**Table 7-7.** Most relevant impact categories for the townhouse and apartment building, identified using screening, simplified, and complete LCA approaches.

Townhouse												
Environmental indicator	Screening LCA			Simplified LCA			Complete LCA					
	Total impact [mPt/m <sup>2</sup> ]	env.	Contribution	Cumulative	Total impact [mPt/m <sup>2</sup> ]	env.	Contribution	Cumulative	Total impact [mPt/m <sup>2</sup> ]	env.	Contribution	Cumulative
GWP	32.6		26%	26%	33.3		27%	27%	35		28%	28%
PM	19		15%	41%	19.2		15%	42%	26		21%	49%
AC	11		9%	50%	11.1		9%	51%	12		9%	58%
WU	15		12%	62%	14.9		12%	63%	15		12%	70%
RD-EF	16		13%	75%	16.5		13%	76%	18		14%	84%
Total	124.2				128.1				140.6			
Apartment building												
Screening LCA			Simplified LCA			Complete LCA						

<b>Environmental indicator</b>	<b>Total impact [mPt/m<sup>2</sup>]</b>	<b>env. Contribution</b>	<b>Cumulative</b>	<b>Total impact [mPt/m<sup>2</sup>]</b>	<b>env. Contribution</b>	<b>Cumulative</b>	<b>Total impact [mPt/m<sup>2</sup>]</b>	<b>env. Contribution</b>	<b>Cumulative</b>
GWP	26.6	27%	27%	27.2	28%	28%	29.8	30%	30%
PM	19.5	20%	47%	19.9	20%	48%	22.5	23%	53%
AC	7.8	8%	55%	8.1	8%	57%	8.7	9%	62%
WU	7.6	8%	63%	7.7	8%	64%	7.8	8%	70%
RD-EF	12.3	13%	76%	12.9	13%	78%	14.4	15%	85%
Total	97.6			101.7			112.8		

Table 7-8 presents the GWP (carbon footprint) and total environmental impact results, along with the corresponding improvements, for all studied strategies across the three LCA methodologies. For the townhouse, Strategy 4 consistently achieves the highest GWP reduction, followed by Strategies 3 and 2. While minor deviations exist between LCA approaches, the differences are generally small: for example, the screening LCA result for Strategy 4 differs from the complete LCA by approximately 4%, whereas differences for other strategies are within 1–2%. When all strategies are combined, all LCA methods yield nearly identical improvement results (44–45%). In terms of total environmental impact, all LCA approaches identify Strategy 4 as the most effective. However, differences arise in the ranking of subsequent strategies. The simplified LCA ranks Strategy 2 as second and Strategy 3 as third, whereas the complete LCA ranks Strategy 1 second and Strategy 3 third. The screening LCA, in contrast, maintains the same hierarchy as for GWP (Strategy 4, followed by 3 and 2). Thus, while all methodologies agree on the most effective strategy, discrepancies exist in the ranking of secondary strategies when total environmental impact is considered.

For the apartment building, the results are more consistent. Across both GWP and total environmental impact, simplified and complete LCA rank Strategies 2 and 3 as the second and third most effective after Strategy 4. The screening LCA assigns similar improvement levels to Strategies 2 and 3. Overall, all three LCA methodologies produce a largely consistent hierarchy of strategies for this case study.

**Table 7-8.** Results and improvements of the studied strategies in terms of GWP ( $\text{kgCO}_2\text{-eq/m}^2$ ) and total environmental impact ( $\text{mPt/m}^2$ ) for the townhouse and apartment building, calculated using screening, simplified, and complete LCA approaches.

<b>Townhouse</b>						
<b>Environmental indicator</b>	<b>Screening LCA</b>		<b>Simplified LCA</b>		<b>Complete LCA</b>	
	<b>Results</b>	<b>Improve.</b>	<b>Results</b>	<b>Improve.</b>	<b>Results</b>	<b>Improve.</b>
<b>Reference</b>						
GWP	1254		1280		1344	
Total env. impact	124.2		128.1		140.6	
<b>Strategy 1</b>						
GWP	1254	0%	1279	0.1%	1323	2%
Total env. impact	124.2	0%	128.0	0.1%	131.2	7%
<b>Strategy 2</b>						
GWP	1225	2%	1228	4%	1287	4%
Total env. impact	122.8	1%	123.6	4%	135.9	3%
<b>Strategy 3</b>						
GWP	1178	6%	1213	5%	1260	6%
Total env. impact	122.0	2%	126.1	2%	134.5	4%
<b>Strategy 4</b>						
GWP	792	37%	831	35%	897	33%
Total env. impact	94.2	24%	99.4	22%	112.0	20%
<b>Combined strategy</b>						
GWP	688	45%	713	44%	740	45%

Total env. impact	90.7	27%	92.9	27%	99.6	29%
<b>Apartment building</b>						
<b>Environmental indicator</b>	<b>Screening LCA</b>		<b>Simplified LCA</b>		<b>Complete LCA</b>	
	<b>Results</b>	<b>Improve.</b>	<b>Results</b>	<b>Improve.</b>	<b>Results</b>	<b>Improve.</b>
<b>Reference</b>						
GWP	1022		1047		1144	
Total env. impact	97.6		101.7		112.8	
<b>Strategy 1</b>						
GWP	1022	0%	1041	1%	1136	1%
Total env. impact	97.6	0%	100.7	1%	111.2	1%
<b>Strategy 2</b>						
GWP	1003	2%	1018	3%	1113	3%
Total env. impact	96.5	1%	99.1	3%	110.8	2%
<b>Strategy 3</b>						
GWP	997	2%	1023	2%	1117	2%
Total env. impact	96.9	1%	100.8	1%	111.7	1%
<b>Strategy 4</b>						
GWP	744	27%	774	26%	872	24%
Total env. impact	83.3	15%	88.2	13%	99.4	12%
<b>Combined strategy</b>						
GWP	680	33%	701	33%	793	31%
Total env. impact	79.4	19%	83.5	18%	93.2	17%

### 7.3.6 Discussion on LCA results of two different residential building typologies

Regarding total environmental impact, more than 50% of the total normalized and weighted impacts of both buildings are attributable to the operation stage. However, in the apartment building case under Strategy 4, the operation stage contributes approximately 44% of the total impact score, reducing its share below 50%. Strategy 4, which implements solar photovoltaic panels, is particularly relevant for buildings in Southeast Asia due to the region's high solar energy potential (Lai et al., 2023). Incorporating a broader range of energy conservation measures in future research, such as building envelope improvements, energy-efficient appliances, behavioral interventions, and advanced technologies, could provide further insights.

The operation stage accounts variedly in terms of the total environmental impact over the lifespan of 50 years, 71%, 74%, 68%, and 84% when considered in all the sixteen impact categories, the five most relevant indicators, the three most relevant indicators (GWP, PM, RD-EF), and GWP impact, respectively. A similar pattern is observed for the apartment building. When trade-offs are observed exclusively in the relevant indicators, the studied strategies generally do not produce significant increases or decreases. However, they appear in other indicators that are not identified as the most relevant, where some strategies increase impacts. These variations demonstrate the importance of conducting LCAs using multiple indicators; assessments based on a single indicator or a set of most relevant indicators defined, may overestimate or underestimate the contribution

of specific life-cycle stages. In addition, analyzing results at the module level rather than only the stage level enables clearer identification of drivers behind increases or changes.

Selection of environmental indicators for comparison across screening, simplified, and complete LCA in this study was based on the relevant indicators identified for both buildings and their strategies, together with total environmental impact. Although European standard EN 15978 provides several recommended indicators for building assessment, indicator selection can vary depending on national regulations and study scope (Meex et al., 2018). Furthermore, EeBGuide does not prescribe a specific set of indicators. Using numerous indicators can make interpretation difficult for non-experts such as architects.

When screening LCA is applied to the townhouse, average differences relative to complete LCA range from 1% to 10%, which are lower than those observed for the apartment building (3%–16%). A similar pattern is found for simplified versus complete LCA comparisons: differences range from 0.45% to 7% for the townhouse and from 2% to 12% for the apartment building. However, PM is an exception: deviations for the townhouse (23% screening; 22% simplified) exceed those of the apartment building (13% screening; 11% simplified). Specifically, using screening LCA to estimate GWP results in average deviations of 7% for the townhouse and 12% for the apartment building compared with complete LCA, corresponding to total impact score differences of 10% and 14%, respectively. When simplified LCA is used, these deviations decrease to 5% and 10% for GWP and to 7% and 10% for total impact score.

Comparisons between screening and simplified LCA results show maximum deviations of 6% and 7% for the townhouse and apartment building, respectively, across six scenarios and six indicators. These findings suggest that screening and simplified LCA approaches provide broadly comparable estimates.

Moreover, the results presented in Table 7-6–Table 7-8 indicate that the contribution of the production stage to GWP over the life cycle is consistent across the three LCA methodologies, whereas the contribution of the operation stage is lower in percentage in the complete LCA compared to the screening and simplified approaches because it considers also the construction and end of life phases. In addition, all three methodologies consistently identify the same ranking of the most relevant impact categories. In terms of GWP impact reduction, all LCA methodologies define the same hierarchy of strategies, with Strategy 4 performing best, followed by Strategies 3 and 2. However, when considering total environmental impact, slight differences emerge between the simplified and complete LCA approaches in the ranking of the second- and third-best strategies. Overall, the screening and simplified LCA approaches provide reasonably accurate results, not only in terms of absolute values but also in preserving the relative ranking of strategies, the contribution of life cycle stages, and the identification of key environmental impact categories for both studied typologies.

Although the EeBGuide simplification approaches do not specify expected accuracy levels of screening and simplified LCA relative to complete LCA, literature suggests that deviations up to 30% for screening LCA and 20% for simplified LCA may occur (Meex et al., 2018). For example,

previous studies comparing simplified and complete building LCAs report deviations of 20% and 30% in GWP (Bonnet et al., 2014; Lasvaux et al., 2013). In the present study, maximum deviations for the townhouse reach 23% (screening) and 22% (simplified) for PM impact.

The main driver of this deviation exceeding 20% is the production stage (modules A1–A3), which represents the largest share of embodied impacts and for which several building components were excluded from simplified approaches. In contrast, in the apartment building case, the maximum deviation between simplified or screening and complete LCA is 16% (RD-EF), which remains below 20%.

Regarding the applicability of each methodology, screening LCA is considerably easier to conduct than complete LCA, as it requires fewer types of building data, includes fewer life cycle modules and components, and considers a limited number of impact indicators. It is also less time-consuming in terms of LCI development, LCA modeling, and results analysis and interpretation. This advantage is particularly relevant for large-scale or high-rise buildings, where several building components and life cycle stages are excluded in screening LCA. The time savings between screening and simplified LCA are less pronounced, as these two approaches differ mainly in the inclusion of additional life cycle modules, particularly the end of life stage in simplified LCA, while other criteria remain largely similar. Nevertheless, screening LCA remains a practical solution in situations where supplementary data required for complete LCA are difficult to obtain or require complex and systematic processing.

Conducting a complete LCA requires a high level of data completeness and transparency, which is often challenging to achieve (Gradin & Björklund, 2021; Hollberg, 2016; Lasvaux et al., 2013). This challenge is particularly evident in the Cambodian context, where building LCA is still emerging, data availability is limited, and local expertise remains insufficient. From a user perspective, screening and simplified LCA are relatively comparable in terms of workflow, from data collection to result interpretation, and are both suitable for early design stages when complete data are not yet available (Hollberg & Ruth, 2016; Soust-Verdagner et al., 2016). In contrast, complete LCA is more complex and resource-intensive, especially when applied to multiple case studies, large-scale buildings, or scenarios involving numerous design strategies and environmental indicators. Therefore, when selecting between screening and simplified LCA, screening LCA may be preferred due to its user-friendliness, lower time and resource requirements, and suitability for contexts with limited data and technical capacity.

### 7.3.7 Limitations and recommendations for future comparative LCA studies

The main limitations of this chapter relate to assumptions regarding mandatory building elements and life-cycle modules included in the comparison of LCA detail levels. Building services should be mandatory for complete LCA. However, inclusion of these components was limited by insufficient data and incomplete bills of quantities for the apartment building case.

Building services can account for approximately 10% of total embodied primary energy (El khouli et al., 2015). Another study found that building services were the second-largest contributor to environmental impacts after interior elements in a highly serviced research building (Mirzaie et al., 2020). Nevertheless, compiling bills of materials, life-cycle inventories, and models for such systems is often challenging, particularly when only partial data are available. Even Mirzaie et al. (2020) reported insufficient information in environmental databases for accurately modeling HVAC systems. Hollberg (2016) suggested that embodied impacts of building services remain relatively minor for most residential buildings, although their importance may increase with greater automation (Hollberg, 2016). Future comparative LCA studies should therefore aim to include building service components despite data and modeling challenges.

Another limitation concerns the end of life stage. As circular economy policies increasingly emphasize building longevity, reuse, and recycling (Giorgi et al., 2018), the lack of data for module C3 (waste processing) is significant. Including this module in simplified and complete LCA could provide valuable insights into deviations between methodological levels.

Although this study focuses on comparing LCA detail levels and promoting simplified LCA for early design stages in Cambodia, uncertainty analysis is also recommended but was beyond the scope of this work. When deviations are below 20%, uncertainty analysis is generally advised for simplified LCA (Hollberg, 2016). However, uncertainty data are rarely available in common environmental product databases, and such analyses can be complex for non-experts. Clear strategies for treating and communicating uncertainty to decision-makers and designers remain limited.

Finally, because this study selected only relevant environmental indicators identified within its scope, future research could incorporate a broader set of indicators recommended in standards such as EN 15978, including EUf, EUm, EUt, OD, and POD, particularly when applying the EF 3.0 impact assessment method for simplified LCA.

## 7.4 CHAPTER CONCLUSION

This chapter consolidates the LCA results of both building case studies: a townhouse and a high-rise apartment building in Cambodia. Over the same 50-year lifespan, the apartment building produces 95% higher GWP than the townhouse. After normalization and weighting of the LCIA results, the total environmental impact of the apartment building is 94% higher than that of the townhouse. However, when comparing impacts per unit of floor area, both the total environmental impact and GWP of the townhouse are approximately 1.2 times higher than those of the apartment building.

The contributions of the sixteen impact categories to overall life-cycle environmental performance were analyzed in depth to identify the main drivers, defined as the most relevant impact categories. These were determined to be climate change (GWP), particulate matter (PM), fossil resource use (RD-EF), acidification (AC), and water use (WU) for both buildings when

toxicity-related indicators were excluded from the hotspot analysis. Therefore, these indicators—derived from results for both residential typologies—can be recommended for future LCA studies in the Cambodian building sector, particularly when evaluating a larger number of indicators is impractical or when single-indicator assessments are to be avoided. When these relevant indicators were assessed exclusively, none of the four strategies showed increases across these categories. This reinforces the interest in the selected strategies to improve the environmental quality of buildings in Cambodia.

Trade-offs among impact categories were also investigated. Although changes occurred in seven of the sixteen categories, after combining all strategies only two indicators still showed increases: land use (LU) and resource use - minerals and metals (RD-MM). The primary drivers of these increases were life-cycle modules A1 and A3 (material acquisition and manufacturing) associated with timber structures and module B6 (operational energy use) related to solar energy generation, which influenced LU and RD-MM impacts, respectively.

A comparative analysis of screening, simplified, and complete LCA approaches was conducted across two residential typologies, six indicators (five impact categories plus the total environmental impact score), and six scenarios (reference plus five strategies). Direct comparisons between screening and simplified LCA show maximum differences of only 3–5% and average differences of 2–3%, indicating strong consistency between the two simplified approaches. In contrast, comparisons between screening and complete LCA reveal maximum deviations of approximately 16–23% and average deviations of about 9–11%. Only one case exceeds 20%: the particulate matter (PM) impact in the townhouse, where deviations reach 22% and 23% for simplified and screening LCA, respectively. Considering multiple impact indicators and scenarios, the differences are generally higher for the apartment building than for the townhouse, except for the PM indicator.

Overall, this study demonstrates that screening and simplified LCA can serve as practical tools for the preliminary estimation of building environmental impacts. Both methodologies enable the identification of consistent hierarchies of strategies for improving green building design and can be effectively used to select the most relevant strategies for the production and operation stages across the two residential building typologies. In particular, screening LCA appears to be easier to apply and more user-friendly than simplified LCA. Its application facilitates the rapid testing of decarbonization strategies during the design phase, thereby supporting more informed decision-making in the construction sector. The development of simplified LCA tools and platforms tailored to local architects and decision-makers in Cambodia is therefore recommended. Future research should further investigate the deviations between LCA simplifications and complete LCA approaches, with particular attention to accuracy and uncertainty analysis.

# 8

## Discussion

This chapter synthesizes and critically discusses the key findings derived from the research methodology and the results presented in the four preceding chapters. It builds upon these findings to address the research questions and incorporates additional relevant insights where appropriate. The discussion confronts and combines the literature point of view, contextual insights from construction professionals, and environmental performance outcomes derived from LCA of case studies, to develop integrated recommendation for green building design in Cambodia. It examines green building strategies identified for the Cambodian context and evaluates the applicability of LCA simplification approaches as design-support tools for green residential buildings. Finally, the discussion includes a reflection on the potential influence of methodological choices, modelling assumptions, and research limitations on the research results.

## 8.1 INTRODUCTION

This chapter synthesizes and critically discusses the findings from Chapters 4 to 7 in relation to the research questions and objectives. As outlined in the methodological framework (Figure 3-1), the study adopts a mixed-methods design in which qualitative and quantitative components are conducted and presented independently, with integration occurring at the stage of interpretation. Accordingly, this chapter brings together results from both approaches to develop a comprehensive understanding and recommendation of green building strategies in Cambodia from two complementary perspectives: contextual insights from construction professionals and environmental performance outcomes derived from LCA. The discussion is structured around the study's key themes, including definitions and characteristics of green building and affordable housing in Cambodia, their integration into design practice, environmental impacts of residential buildings, strategies for reducing life cycle impacts, and the application of simplified LCA as a design-support tool. Rather than merging datasets, the chapter critically examines how the separate findings collectively address the research questions. The discussion also includes a reflection on methodological choices, data limitations, and modelling assumptions, highlighting their influence on interpretation. The chapter concludes by outlining key limitations of the work presented.

## 8.2 DEFINITIONS AND CHARACTERISTICS OF AFFORDABLE HOUSING AND GREEN BUILDING IN CAMBODIA

The findings reveal that the definitions and characteristics of affordable housing and green building in Cambodia are shaped by contextual, socio-economic, and professional perspectives and practices, rather than strictly adhering to standardized global frameworks. Construction professionals provided diverse and insightful interpretations related to the architectural design and construction of affordable housing, reflecting not only technical considerations but also socio-cultural values. Affordable housing in Cambodia is primarily understood as housing that ensures economic accessibility, particularly for low- to middle-income households. Key characteristics consistently identified include affordability in terms of purchase price, improved quality of life, comfort, and security. These findings align with previous studies that emphasize affordability as a function of both cost and livability (GGGI et al., 2022; Kul et al., 2024; Long et al., 2024; Traub & Sweeting, 2020). More precisely, defining affordable housing as housing targeted at low- and middle-income groups provides greater contextual relevance than the broader notion of “housing for all”. Importantly, participants extended the definition of affordability beyond purely financial metrics to include accessibility to public facilities, infrastructure, and economic opportunities. This broader interpretation indicates that affordability in Cambodia is closely linked to urban planning, user needs, and integration within the local built environment and cultural context. These perspectives reinforce the understanding that housing affordability cannot be assessed solely based on price thresholds but must also consider overall living conditions, as shaped by construction stakeholders.

Similarly, green building definitions in Cambodia are not strictly aligned with international principles or standardized practices but are instead adapted to local conditions and practical constraints. Flexibility in applying green building principles is emphasized, acknowledging that full compliance with global frameworks is often unrealistic in developing contexts. This pragmatic approach reflects limitations in technical capacity, financial resources, and regulatory enforcement, while also demonstrating adaptability to real-world conditions (Abdelkhalik & Azmy, 2022; S. Ali et al., 2026; Pekdogan, 2024). Despite these constraints, core elements of green building (Nduka & Ogunsanmi, 2015; Ragheb et al., 2016) such as architectural and construction strategies, resource and energy efficiency, and environmental protection are widely recognized. In addition, participants identified context-specific characteristics, including flood resilience, bioclimatic design, integration of greenery, and consideration of end-user well-being. These findings highlight the importance of climate-responsive and culturally adapted design strategies in tropical regions such as Cambodia. However, some misconceptions persist within the sector. A minority of participants associated green building exclusively with high-rise developments. Although this perception was not dominant, addressing such misconceptions remains important for promoting broader adoption of green building practices across diverse building typologies.

Overall, the findings suggest that both affordable housing and green building concepts in Cambodia are evolving, context-dependent, and strongly influenced by professional experience. This underscores the need for locally grounded guidelines, increased implementation of pilot projects as case studies, and further research to advance knowledge in these areas. Although self-reported awareness among the surveyed professionals is relatively high, this may reflect the study's selection criteria, including prior interest in green building. Continued efforts are needed to ensure this awareness translates into consistent and effective practice.

### **8.3 MAIN FOCUS FOR DESIGNING GREEN AFFORDABLE HOUSING**

The integration of green building principles with affordable housing presents both opportunities and challenges within the Cambodian construction sector. The findings indicate that designing green affordable housing requires balancing cost constraints with the achievement of sustainable building performance, a challenge frequently highlighted by construction professionals worldwide (Adabre et al., 2020; Reid, 2023). A key insight from the study is the identification of multi-dimensional design priorities, including architectural design and construction techniques, material selection, bioclimatic design, end-user quality of life, resource-saving practices, integration of greenery, cost considerations, and residential typologies. Among these, architectural design and construction techniques ranging from conceptual design to construction quality, and material selection play a critical role in achieving both affordability and sustainability.

In addition to general material categories identified by participants, such as local, recycled, affordable, and environmentally friendly materials, specific materials were recommended, including clay bricks and earth, wood and bamboo, concrete and lightweight concrete. These

materials are perceived as cost-effective, locally available, and potentially lower in environmental impact compared to imported or highly industrialized alternatives. However, the LCA of the two case studies showed that materials with the highest environmental impacts include reinforcing steel, concrete, and ceramic tiles. It could therefore be useful to present the results of various buildings LCA to a wide audience of professionals, in order to continue to improve the environmental knowledge of professionals in Cambodia related to materials environmental impacts.

Moreover, tensions between affordability and sustainability remain evident. Some construction professionals perceive green building as inherently costly, which can hinder its adoption in affordable housing projects, particularly in the Cambodian context. This divergence highlights a lack of consensus within the sector and underscores the need for evidence-based approaches, including the promotion of local materials, traditional practices, and context-adapted green building strategies.

Cost and housing price emerged as central considerations in supporting the development of green affordable housing. While the findings align with national affordable housing development programs, they primarily reflect the perspectives of construction professionals rather than developers or real estate stakeholders. Affordability can be addressed through two main pathways: optimization of design and construction practices, as suggested by participants, and financial or policy support from government and non-governmental organizations. Government policies and market conditions play a crucial role in shaping affordability outcomes (Galster & Lee, 2021). Although national programs aim to promote affordable housing, developers may face challenges related to limited profit margins and cost control. In the absence of strong regulatory frameworks, market dynamics may dominate, potentially leading to increased housing prices and reduced affordability. This highlights the need for institutional support mechanisms, including incentives, regulations, and public-private partnerships, to facilitate the development of green affordable housing.

Residential typology is another critical factor influencing design strategies. High-rise and medium-rise apartments are increasingly favored in urban areas due to land constraints and population density, even though family housing is still commonly recommended by professionals. Other typologies, such as shophouses, remain relevant in specific contexts. These findings suggest that no single typology is universally optimal; instead, design solutions must be adapted to local conditions and urban dynamics. In summary, designing green affordable housing in Cambodia requires an integrated approach that considers technical, economic, environmental, institutional, and social dimensions. Such an approach should be supported by context-specific strategies, stakeholder collaboration, and alignment between policy objectives and market practices.

## 8.4 TOWARD SUSTAINABLE BUILDING IN CAMBODIA FROM A LIFE CYCLE PERSPECTIVE

### 8.4.1 The environmental impacts of residential buildings in Cambodia

The LCA results presented in Chapters 5, 6, and 7 provide quantitative evidence of the environmental impacts associated with residential buildings in Cambodia. Across both townhouse and apartment case studies, the operation and production stages were identified as the dominant contributors to total life cycle impacts. The operation stage is primarily driven by electricity consumption, while the production stage is largely influenced by raw material extraction and manufacturing processes. Approximately 10 to 13 out of the 16 environmental impact categories evaluated, representing more than 50% of the total environmental impact (expressed in millipoints), are dominated by the operation stage. This confirms its critical role in overall building performance. These findings are consistent with results reported in previous studies, both in the literature and within similar regional contexts (Kua & Wong, 2012; Le et al., 2021a; Rashid et al., 2017; Satola et al., 2021; Viriyaraj et al., 2024). However, the relative magnitude of contributions across life cycle stages may vary depending on national energy mixes, building conditions, and the specific environmental indicators considered (Nematchoua et al., 2020). While comparisons with other studies are useful for validation, differences in system boundaries, data sources, and methodological assumptions limit direct comparability and highlight the need for more harmonized approaches.

Further analysis of building components and materials reveals their significant contributions to environmental impacts. Based primarily on the apartment building case study, structural elements, foundation systems, and finishing materials were identified as the main contributors across multiple impact categories. Correspondingly, reinforcing steel, concrete, and ceramic tiles were found to be the most impactful materials. Although this analysis is derived from the apartment building, both case studies share similar construction methods and material profiles, allowing for broader interpretation of these findings within the Cambodian context. These results emphasize the importance of material selection, optimization, and potential substitution, as well as renovation strategies, in reducing environmental impacts. Both case studies represent common residential typologies in Cambodia and align with findings from Chapter 4, where high-rise apartments and shophouses were identified as prevalent housing forms.

As one of the first building LCA studies conducted in Cambodia, this research establishes a benchmark for future assessments and contributes to the development of life cycle inventory data in the region. It also highlights the need for localized LCA databases, tools, and methodologies to improve the accuracy and relevance of environmental assessments in developing countries, particularly in Southeast Asia. Importantly, this study evaluates sixteen environmental impact categories, which represents a relatively comprehensive approach compared to studies focusing on a limited number of indicators. However, such breadth may complicate interpretation, particularly for non-experts. Therefore, the use of aggregated indicators, such as total

environmental impact (single score), is valuable for supporting decision-making by architects and engineers. In addition, the identification of key impact categories, such as global warming potential, particulate matter, fossil resource use, water use, and acidification, provides useful guidance for targeted interventions. Nonetheless, further validation using region-specific data and methodological frameworks is necessary, as the characterization, normalization, and weighting methods applied are based on international standards.

#### 8.4.2 Building design strategies aiming to reduce life cycle impact

This study evaluated multiple building design strategies aimed at reducing life cycle environmental impacts, based on the research objectives, feasibility considerations, and existing literature. The effectiveness of these strategies varies depending on their application to different case studies and building typologies, as well as their focus on material use, energy consumption, or both.

Material-related strategies, including optimization of material use, reduction of finishing materials, and substitution with more environmentally friendly or bio-based materials (e.g., timber), demonstrated varying levels of effectiveness. In the townhouse case, these strategies (Strategies 1-3) resulted in more significant impact reductions compared to the apartment building case. This difference reflects variations in building scale, material intensity, and structural requirements. In contrast, the implementation of renewable energy systems, particularly solar PV panels (Strategy 4), resulted in substantial reductions in environmental impacts for both case studies. When assessed using both GWP and total environmental impact, Strategy 4 consistently demonstrated the highest individual reduction potential.

Among the evaluated strategies, two were identified as the most effective: (i) the integration of renewable energy through solar PV systems (Strategy 4), and (ii) the use of lightweight timber frame walls as a substitute for conventional masonry walls (Strategy 3). These strategies achieved significant reductions in both GWP and total environmental impact. Furthermore, when all strategies were combined, the results showed even greater reductions, ranging from approximately 32-47% in GWP and 18-30% in total environmental impact across both case studies. These findings highlight the importance of adopting integrated design approaches that combine multiple strategies to maximize environmental benefits. They also provide a basis for future research, particularly in exploring the scalability of these strategies across different building typologies and contexts in Cambodia. Given the strong performance of solar PV systems, policy implications, such as incentives for renewable energy adoption, are particularly relevant.

However, the analysis also reveals trade-offs associated with certain strategies. Despite overall reductions in environmental impacts, increases were observed in specific indicators, including land use, resource depletion (minerals and metals), and human toxicity (non-cancer effects). These trade-offs are primarily associated with life cycle modules A1-A3 (material production, particularly timber in Strategy 3) and B6 (operational energy in Strategy 4). These findings underscore the importance of evaluating environmental performance across multiple indicators

and life cycle stages, rather than focusing solely on a limited number of commonly used metrics. They also highlight the need for mitigation measures, such as sustainable sourcing of materials (e.g., certified timber) and careful consideration of material supply chains. Overall, the results demonstrate that while certain strategies can significantly reduce environmental impacts, a comprehensive and balanced assessment is essential to avoid unintended consequences. This reinforces the value of LCA as a tool for identifying both benefits and trade-offs in sustainable building design.

## 8.5 LCA SIMPLIFICATION AS A DESIGN-SUPPORT TOOL

The application of LCA simplification approaches, namely screening LCA and simplified LCA, in this study demonstrates their potential as practical tools for supporting sustainable building design from a life cycle perspective, particularly in contexts characterized by limited data availability and technical capacity. The comparison between simplified, screening, and complete LCA results indicates that these approaches can provide reasonably accurate estimates, with deviations generally within acceptable ranges. LCA simplification approaches are also recognized by other international studies as useful to compensate the lack of availability of local data (Wittstock et al., 2012; Decorte et al., 2021; Rossi et al., 2012). Given that the EeBGuide does not specify explicit acceptable deviation thresholds, the results of this study were evaluated against values reported in the literature, namely 30% for screening LCA and 20% for simplified LCA (Bonnet et al., 2014; Lasvaux et al., 2013). Most impact categories fall within these ranges. However, particulate matter represents an exception, with deviations of 23% (screening LCA) and 22% (simplified LCA) compared to complete LCA, slightly exceeding the suggested threshold for simplified approach. These findings provide a useful reference for future comparative studies, as this research reports deviations across three LCA levels, six environmental indicators, and two building typologies.

Despite these deviations, screening and simplified LCA methods demonstrate strong consistency in the relative ranking of design strategies, life cycle stages, and key impact categories. Although absolute values may differ from complete LCA results, both simplification approaches produce comparable trends and hierarchies of results. This consistency confirms their reliability for comparative analysis and decision-making. Furthermore, the results obtained from screening and simplified LCA are themselves closely aligned, indicating that both approaches are broadly comparable in practical applications.

However, deviations may be influenced by methodological limitations, particularly the exclusion or inclusion of certain life cycle modules and building components. For instance, screening LCA does not consider the end of life stage, while simplified LCA may include additional modules such as waste processing (module C3). Similarly, the omission of building service systems in the complete LCA due to data limitations may affect the accuracy of comparisons. These aspects highlight important limitations related to data availability and methodological scope, which are discussed further in the subsequent section.

From a practical perspective, screening and simplified LCA approaches are significantly easier to implement than complete LCA. This is primarily due to reduced data requirements, particularly for building components and life cycle inventory inputs. Both approaches rely mainly on data related to material production and operational energy use, which are generally more accessible. Screening LCA is the most straightforward method, as it excludes the end of life stage, making it particularly suitable for rapid assessments. Simplified LCA, while slightly more demanding, provides a more comprehensive evaluation by including additional life cycle stages. This requires more time for data collection and modeling, especially when multiple design alternatives are assessed. Nevertheless, it offers added value for practitioners who wish to consider end of life impacts, particularly in the context of circular economy principles. However, the availability and reliability of such data remain limited, and the application of these methods may still depend on assumptions or secondary data sources. These challenges are not unique to simplified LCA but also affect complete LCA.

Overall, the findings are particularly relevant for developing countries such as Cambodia, where conducting full LCAs is often constrained by limited data, resources, and technical expertise (Gradin & Björklund, 2021; Hollberg, 2016; Lasvaux et al., 2013; Ruf et al., 2022). Screening LCA provides an accessible entry point for integrating environmental considerations into early-stage design decision-making (Hochschorner & Finnveden, 2003). Importantly, the study demonstrates that screening LCA is effective in identifying relative differences between design options, even if absolute values differ from more detailed approaches. As such, simplification LCA approaches can be effectively integrated into the building design process as decision-support tools. They enable designers, architects, engineers, and students to evaluate low-impact strategies, compare alternatives, and promote sustainable practices within practical constraints. By bridging the gap between complex analytical methods and real-world application, simplification LCA plays a critical role in advancing sustainable construction in resource-constrained contexts.

## 8.6 RESEARCH METHODS AND CASE-STUDY LIMITATIONS

As discussed in Chapters 4 to 7, the primary limitations of this research are consolidated and critically examined in this section. These limitations relate to the scope of the study, data availability, methodological constraints, and the applicability of findings.

Regarding the integration of green building and affordable housing in Cambodia, a key limitation concerns the analysis of construction cost and housing price. The study does not fully account for several important factors, such as the definition of standardized floor areas for green affordable housing, which would enable more consistent cost comparisons. In addition, the analysis does not incorporate broader socio-economic indicators, including average household income, monthly salaries, and rental market conditions. These factors are essential for evaluating housing affordability in a comprehensive manner, particularly in the Cambodian context. This limitation is primarily due to the methodological focus of the study, which emphasizes the perspectives of construction professionals rather than those of housing users, developers, or real estate stakeholders. While the findings align with national housing development programs, broader

stakeholder involvement would enhance the robustness and applicability of the results. Furthermore, analyzing housing markets and pricing mechanisms requires expertise in economics and real estate, which falls beyond the primary scope of this research. Nevertheless, the findings provide indicative insights into construction costs and potential pricing strategies for green affordable housing, supporting practitioners in aligning their projects with policy objectives and affordability targets.

In relation to the LCA component of the study, a major limitation concerns the availability and quality of data for LCI analysis and modeling. Due to the lack of detailed building documentation and technical specifications, the study relied partially on data from the literature and necessary assumptions. This constraint also required the use of supporting data collection methods, such as on-site observations and consultations with professionals (Mirzaie, 2022; Rashid et al., 2017). The challenges encountered highlight the importance of developing data management systems and digital tools, such as Building Information Modeling (BIM) (Feng, 2020), to facilitate efficient material tracking, bill of quantities generation, and LCI data collection.

Given that this is one of the first building LCA studies conducted in Cambodia, the use of assumptions is unavoidable. The study underscores the importance of comprehensive and reliable data for conducting cradle-to-grave assessments. In particular, the exclusion of the end of life stage, specifically module C3 (waste processing), represents a limitation due to the absence of data on demolition practices, recycling potential, and waste management systems in Cambodia. Although previous studies suggest that this stage contributes relatively little to total environmental impact (Nematchoua et al., 2022; Sharma et al., 2011), its inclusion could be important in the Cambodian context, especially in relation to circular economy strategies and the use of recycled materials in low-cost housing (Giorgi et al., 2018).

Another limitation relates to the use of international databases and impact assessment methods. While the study evaluates a comprehensive set of sixteen environmental impact categories, the reliance on non-localized data may affect the accuracy and contextual relevance of the results. This highlights the urgent need to develop country-specific databases, including emission factors for locally produced construction materials, to improve the reliability of LCA studies in Cambodia.

With respect to the evaluated design strategies, certain limitations are also identified. The use of timber was limited to structural elements and window frames. Extending their usage to additional building elements could further enhance building environmental performance. Notably, various types of timber buildings have already been constructed in developed countries (Bahrami et al. 2024), including Japan. Moreover, the study does not include detailed assessments of structural performance, material durability, or cost-benefit analysis for the proposed material substitutions. Although thermal performance was considered to ensure comparable operational conditions, further investigation is required to assess structural feasibility and safety, particularly for strategies involving timber construction. Issues such as fire resistance, load-bearing capacity, and long-term durability should be addressed in future research. In addition, integrating economic analysis would enhance the practical applicability of the strategies by linking environmental

performance with financial feasibility, which is particularly important in developing country contexts.

In the comparative LCA analysis, limitations arise from differences in system boundaries and the inclusion of life cycle stages and building components across screening, simplified, and complete LCA approaches. For example, the exclusion of building services in the complete LCA due to insufficient data may affect the accuracy of comparisons with simplified approaches, where such components are treated differently. Similarly, the absence of data for certain end of life modules limits the completeness of the assessment. These constraints highlight the need for improved data collection practices and greater availability of detailed building information, particularly for building services in mid- to high-rise developments.

Finally, the comparison between LCA approaches in this study is based on six environmental indicators. While this provides valuable insights, further research could extend the analysis to additional indicators to assess whether similar deviation patterns are observed. Expanding the scope of comparison across more indicators, scenarios, and building typologies would strengthen the generalizability of the findings. However, such extensions would require significant additional time and computational effort. Despite these limitations, the study provides a valuable foundation for understanding the applicability of simplification LCA approaches and supports their integration into green building design practices in Cambodia.

## 8.7 CHAPTER CONCLUSION

Overall, this chapter demonstrates that the research findings are intrinsically linked to the quality of data, the methodological choices, and the analytical tools applied throughout the study, as well as to comparisons with relevant existing studies. The use of qualitative insights from construction professionals and quantitative LCA results has enabled a comprehensive and context-sensitive analysis, while maintaining the independence of each methodological approach.

The findings related to the definitions, characteristics, and key aspects of green building, affordable housing, and their integration provide valuable insights for the Cambodian construction sector. These results contribute to a clearer understanding of how sustainability and affordability can be addressed within local socio-economic and professional contexts. In parallel, the LCA results from the case studies not only establish an initial benchmark for the environmental performance of residential buildings in Cambodia but also identify design strategies with significant potential to reduce life cycle impacts. These quantitative findings complement the qualitative results by providing measurable evidence to support sustainable design decisions.

Furthermore, the introduction and evaluation of simplification LCA approaches, particularly screening LCA, demonstrate their practical applicability as design-support tools during early project stages. These approaches offer a feasible pathway for integrating life cycle thinking into building design processes, especially in contexts with limited data and technical capacity.

At the same time, the identified limitations including the scope of stakeholder involvement, data availability, system boundaries, and tool applicability highlight important areas for further research and methodological improvement. Future work should focus on expanding empirical datasets, strengthening local data infrastructures, refining low-impact design strategies, and improving the accessibility and usability of LCA tools for practitioners. Such efforts are essential to support the advancement of green building practices in developing countries such as Cambodia.

# 9

## Conclusion

This final chapter synthesizes the key findings and major contributions of the research, with particular emphasis on its innovative aspects and original contributions to the field. It also discusses the main limitations identified throughout the study and reflects on their implications. In addition, the chapter provides a critical reflection on the research process and offers recommendations for future research directions.

## 9.1 SYNTHESIS

The challenges and limitations associated with green building adoption in Cambodia, particularly in relation to energy and material efficiency, remain insufficiently addressed within the construction sector. This issue cannot be overlooked, especially in light of the current construction boom, which is expected to significantly increase greenhouse gas emissions and environmental impacts in the near future. This context underscores the urgency of integrating sustainability considerations throughout the entire building life cycle, from design to end of life, in order to mitigate environmental impacts and promote the adoption of green building practices aligned with sustainable development principles.

This thesis aims to identify green building design strategies based on the perspectives of local construction professionals and a life cycle approach, while also examining the applicability of simplified LCA tools to support the evaluation of environmental impacts during the design stage. The research questions, as outlined in the Introduction chapter, guided the development of the research methodology and the overall structure of the study.

A mixed-methods research approach was adopted, combining qualitative and quantitative methods to address the research objectives comprehensively. First, a thorough literature review was conducted to establish a theoretical foundation and refine the research questions. This was followed by a survey of construction professionals in the Cambodian construction sector, which provided insights into current practices related to green building and affordable housing. The survey also highlighted context-specific definitions, characteristics, and key considerations from the perspective of industry practitioners, offering valuable guidance for the future development of integrated green affordable housing strategies.

The LCA framework was incorporated into the study due to its recognized importance in evaluating environmental performance in the built environment. Through the application of LCA, the study assessed the environmental impacts of two conventional residential building typologies in Cambodia and evaluated a range of design strategies aimed at reducing life cycle impacts. The results provide an overview of the environmental burdens associated with local construction practices, while also demonstrating the applicability of LCA methodologies in the Cambodian context. As such, this study contributes to informing stakeholders about the environmental implications of building materials and components and establishes a preliminary benchmark for building LCA in Cambodia. Furthermore, the LCA analysis was extended to assess multiple design strategies incorporating both material- and energy-related scenarios. These scenarios enabled the identification of potential pathways for reducing environmental impacts and emissions, highlighting the most effective strategies for improving building sustainability performance.

Given the study's context within a developing country where limitations in data availability and technical expertise are significant, the introduction of LCA simplification approaches is particularly relevant. By comparing three levels of LCA; screening, simplified, and complete, the study demonstrates that screening LCA represents the most accessible and practical method. It

can serve as an effective decision-support tool during the early design stages, enabling practitioners to estimate environmental impacts and evaluate alternative design strategies with limited data requirements.

Overall, the findings of this thesis address the established research objectives and contribute to advancing sustainable development and green technology adoption in Cambodia's construction sector. The results provide both theoretical and practical insights that can support policymakers, designers, and industry professionals in promoting environmentally responsible building practices. The main findings from the preceding chapters are summarized in the following sections.

## 9.2 ORIGINAL CONTRIBUTIONS

### 9.2.1 Contextual characteristic of affordable housing in Cambodia

The affordable housing sector plays a critical role in Cambodia's socio-economic development while also contributing to the advancement of environmental sustainability within the construction industry. The findings of this study indicate that residential construction represents the dominant building typology in the Cambodian context, with strong involvement from local construction professionals, including architects, civil engineers, green building experts, and decision-makers, followed by participation in commercial building projects. Given their diverse professional backgrounds, levels of experience, and areas of expertise, these stakeholders demonstrate varying interpretations of the concept of affordable housing. Nevertheless, the results show that most respondents are familiar with the concept, and a significant proportion have practical experience in designing affordable housing projects. Consequently, their self-reported knowledge levels can be considered reasonably well-developed, albeit unevenly distributed across professional groups.

This study makes an original contribution by establishing a contextualized definition and set of characteristics of affordable housing in Cambodia, as perceived by construction professionals. These findings provide practical guidance for industry practitioners, as well as for architectural and civil engineering students. Furthermore, they offer a useful reference for future research and academic instruction in the field.

According to the study results, the key characteristics of affordable housing in Cambodia include:

- Architectural design and construction techniques that emphasize functional space planning, adequate housing quality, minimalistic design, community integration, adaptation to local culture and vernacular architecture, and the incorporation of sustainable design principles;
- Affordability, reflected in accessible pricing for target users;
- Enhancement of quality of life for occupants;
- Appropriate location, typically in suburban areas and away from high-risk zones;

- Targeting low- to middle-income households;
- Thermal and spatial comfort;
- Use of affordable and locally available materials;
- Inclusivity, promoting housing access for a broad segment of the population;
- Energy efficiency, particularly through reduced energy consumption;
- Accessibility to public services and facilities;
- Safety and security considerations.

In terms of economic parameters, the study identifies a typical construction cost ranging from USD 250–300/m<sup>2</sup> (based on median values), while sale prices exhibit greater variability, ranging from USD 400 to 840.5/m<sup>2</sup>. These figures align broadly with the commonly observed construction cost range of USD 250–375/m<sup>2</sup> in the Cambodian context. The study also highlights several prominent affordable housing projects frequently cited by respondents, including Arakawa Residence, Serey Mongkul Satellite City, and the 100 Houses Project. These examples serve as practical references for current implementation and future development of affordable housing initiatives in Cambodia.

### 9.2.2 Contextual characteristics of green building in Cambodia

The concept of green building design is generally well recognized among construction professionals in Cambodia. However, variations in self-reported knowledge levels were observed across professional groups. In particular, construction engineers reported comparatively lower levels of familiarity, whereas architects, green building experts, and decision-makers demonstrated a stronger understanding of green building principles. Despite these differences, the study reveals that the definitions and characteristics of green building in the Cambodian context are diverse yet coherent, reflecting both global sustainability principles and local considerations. Based on the perspectives of respondents, the key characteristics of green building design in Cambodia include:

- Architectural design and construction techniques that integrate sustainable design principles, environmentally responsible construction methods, and eco-friendly approaches. These also emphasize practical and functional space planning, integration with site and surroundings, adaptation to local culture and social context, ease of maintenance, minimalistic design, and resilience to environmental risks such as flooding;
- Resource efficiency, including the reduction of energy, water, material consumption, land use, maintenance, and costs;
- Material strategies, focusing on the use of reused and recycled materials, low-carbon and environmentally friendly products, as well as locally sourced and natural materials;
- Bioclimatic design approaches, promoting natural lighting and ventilation;
- Integration of greenery within and around the building environment;
- Occupant-centered considerations, including thermal comfort, well-being, social interaction, and safety;
- Minimization of environmental impacts across the building life cycle;

- Use of renewable energy systems;
- Alignment with the pillars of sustainable development (environmental, social, and economic);
- Waste management strategies;
- Green building certification frameworks, where applicable.

From an economic perspective, the study identifies that construction costs for green buildings range from approximately USD 290 to 600/m<sup>2</sup>, while sale prices show wider variability, ranging from USD 500 to 1,587/m<sup>2</sup>, based on median values reported by respondents. These variations reflect differences in design strategies, material selection, and levels of sustainability integration. In terms of practical examples, several green residential building projects in Cambodia were frequently cited by respondents. Among these, the Rose Apple Square development was mentioned most consistently, indicating its relative prominence as a reference project within the local context.

### 9.2.3 Green affordable housing design

Based on the perspectives, professional experience, and current practices of construction stakeholders in Cambodia, this study identifies key aspects of green affordable housing design through the integration of green building principles and affordable housing concepts. These findings provide contextually grounded guidance for architects, engineers, and other construction professionals, supporting the effective design and development of green affordable housing adapted to local conditions. The results indicate that most professional groups consider green building design and affordable housing to be compatible and recognize the potential for integrating these two concepts. However, some construction engineers expressed skepticism, viewing them as unrelated due to perceived cost and implementation challenges. Despite these differing viewpoints, the study provides practical and context-specific insights that demonstrate the feasibility of integrating sustainability and affordability in the Cambodian context.

Through a detailed analysis of stakeholder perspectives, the study identifies several key considerations and recommendations for green affordable housing design in Cambodia:

- Architectural design and construction techniques, including the provision of community and shared spaces, application of sustainable design principles, minimalistic design approaches, compliance with relevant standards, space optimization, building quality, and accessibility;
- Material selection, emphasizing the use of local, reused, recycled, recyclable, natural, eco-friendly, and cost-effective materials;
- Bioclimatic design strategies, promoting passive environmental performance;
- Enhancement of quality of life, including thermal comfort, social interaction, adequate living space, healthy indoor environments, recreational opportunities, and improved living standards;
- Resource and cost efficiency throughout the building life cycle;

- Integration of greenery within the built environment;
- Maintaining affordability as a core design objective;
- Minimization of environmental impacts;
- Integration of renewable energy systems;
- Rainwater harvesting systems;
- Waste management strategies;
- Minimization of construction costs without compromising essential performance.

From an economic perspective, the construction cost of green affordable housing is estimated to range from approximately USD 280 to 400/m<sup>2</sup>, while sale prices vary between USD 500 and 1,000/m<sup>2</sup>, according to median values reported by construction professionals.

In terms of material preferences, the study identifies commonly recommended materials such as wood, concrete, clay, bamboo, earth, and lightweight concrete. Broader material categories include local and recycled materials, eco-friendly bricks, and low-cost alternatives (further detailed in Section 4.2.5). Although preferences vary among professional groups, clay brick emerges as the most favored material, followed by bio-based and recycled materials. The study also highlights the role of various technologies, tools, and design approaches in supporting the implementation of green affordable housing. Additionally, several projects in Cambodia are identified as representative examples of both affordability and sustainability, including Arakawa Residence, Serey Mongkul Satellite City, and the 100 Houses Project.

Regarding building typologies, high-rise apartments are identified as the most preferred option for green affordable housing, followed by medium-rise apartments and shophouses. Detached houses are also considered desirable by some respondents; however, their feasibility is constrained by high land costs in urban areas. Nevertheless, this typology may remain a viable option in locations where land is more affordable, given its continued preference among stakeholders. However, it should be implemented on narrow plots of land in order to avoid falling into the trap of urban sprawl and excessive artificialization of natural land.

#### 9.2.4 LCA of residential buildings in Cambodia

A primary contribution of this thesis from a life cycle perspective is the evaluation and establishment of a benchmark for sixteen environmental impact categories of residential buildings in Cambodia using LCA. Two residential building typologies with different specifications, a townhouse and an apartment building, were assessed within the same system boundary and over a 50-year lifespan.

The results indicate that, in absolute terms, the apartment building generates approximately 95% higher GWP than the townhouse. Similarly, when aggregating all sixteen environmental impact categories, the total environmental impact of the apartment building is approximately 94% higher than that of the townhouse. However, when results are normalized per GFA, the findings differ. The townhouse exhibits a GWP of 1344 kg CO<sub>2</sub>-eq/m<sup>2</sup> and a total environmental impact of 140.6

mPt/m<sup>2</sup>, whereas the apartment building shows a GWP of 1144 kg CO<sub>2</sub>-eq/m<sup>2</sup> and 112.8 mPt/m<sup>2</sup>. This indicates that, on a per-area basis, the townhouse has approximately 20% higher GWP and 15% higher total environmental impact compared to the apartment building.

The results also align with findings from other international contexts, showing that the operational stage is the dominant contributor to environmental impacts, primarily driven by energy consumption. This is followed by the material production stage, which also contributes significantly across most impact categories. A detailed analysis of the apartment building case reveals that the main contributors within the production stage are structural systems, foundation piles, and finishing elements. The materials with the highest environmental impacts include reinforcing steel, concrete, and ceramic tiles. These findings provide critical insights into priority areas for impact reduction in the Cambodian construction sector.

### 9.2.5 Building design strategies to reduce life cycle impacts

To effectively reduce both GWP and overall environmental impacts throughout the building life cycle, this study recommends combining strategies from both material and energy perspectives. The findings demonstrate that integrating at least one material-related strategy (e.g., the use of eco-friendly or bio-based materials) with one energy-related strategy (e.g., renewable energy systems) yields the most significant impact reductions.

Among the strategies evaluated, the two most effective approaches are:

- Replacing conventional masonry walls with lightweight timber frame systems;
- Installing solar photovoltaic (PV) panels to generate renewable energy.

Further improvements can be achieved by combining these strategies with additional measures, such as optimizing material use by reducing finishing and decorative elements, and incorporating environmentally friendly or bio-based materials where feasible. The combined application of all these studied strategies results in substantial environmental benefits. Specifically, GWP reductions of approximately 44% for the townhouse and 32% for the apartment building are achieved. In terms of total environmental impacts, reductions of 30% and 18%, respectively, are observed.

Overall, these findings highlight the importance of integrated design approaches that address both material selection and energy performance. The use of bio-based materials (e.g., timber), low-carbon materials, and environmentally responsible manufacturing processes can significantly reduce impacts associated with traditionally high-impact materials such as reinforcing steel, concrete, and ceramic tiles. In addition, maximizing the integration of solar energy systems through rooftop, façade, or balcony installations, represents a key strategy for achieving low-carbon building design. These recommendations are applicable to both new construction and the renovation of existing buildings, particularly in efforts to improve energy and material efficiency.

### 9.2.6 LCA simplification LCA for building design

Based on the comparative analysis of three levels of LCA detail, namely screening, simplified, and complete LCA, this study demonstrates that the environmental impact results obtained from screening and simplified LCA approaches are broadly comparable. Furthermore, the deviations between these simplified methods and the complete LCA fall within acceptable ranges. Among the approaches evaluated, screening LCA emerges as the most practical and accessible tool for early-stage building design. It enables the preliminary estimation of environmental impacts and facilitates the evaluation of alternative low-impact design strategies with relatively limited data requirements.

The application of screening LCA supports rapid assessment and comparison of design options, thereby enhancing decision-making processes in the Cambodian construction sector, where data availability and LCA expertise are often limited. This approach requires only basic input data, considers a reduced set of building components and life cycle stages, and significantly reduces time and resource demands compared to full LCA. In contrast, complete LCA is more data-intensive, time-consuming, and requires a higher level of expertise, as well as detailed and transparent datasets. Despite its simplified nature, screening LCA provides sufficiently reliable results for early design decision-making and shows strong consistency with simplified LCA outcomes.

Therefore, LCA simplification approaches, particularly screening LCA, are recommended as effective decision-support tools for green building design. They can assist construction professionals and policymakers in integrating environmental considerations into the design process and in promoting more sustainable building practices in Cambodia.

## 9.3 OVERALL CONCLUSIONS

The overall aim of this research was to identify green building design strategies, informed by local construction professionals and supported by building LCA, for the development of green affordable housing in Cambodia. In summary, the study has identified key contextual and practical aspects of both green building and affordable housing, as well as their integration within the Cambodian context. These include core considerations for green affordable housing design, ranging from architectural design and construction techniques to material selection and preferred residential typologies. The findings provide a comprehensive framework to guide practitioners in incorporating sustainability principles while maintaining affordability.

In addition, the environmental performance of representative residential buildings was evaluated using LCA, demonstrating that life cycle environmental impacts are significant and vary across building typologies and components. The results highlight the importance of implementing effective design strategies, particularly those related to material selection and energy use, to reduce overall environmental impacts. These strategies were systematically assessed within the LCA framework, reinforcing their relevance and applicability in practice. The integration of

stakeholder-informed design strategies with LCA-based evaluation underscores the value of combining qualitative and quantitative research approaches. This complementary methodology strengthens the reliability of the findings and demonstrates the practical significance of green building strategies for architectural design and construction in Cambodia.

Overall, the study shows that the proposed green building design strategies, together with approaches aimed at reducing life cycle impacts and the introduction of simplification LCA methods, have strong potential to contribute to environmental impact reduction in the Cambodian construction sector. These contributions are aligned with national policies and sustainability initiatives, and they support the broader transition toward sustainable construction practices. Furthermore, the adoption of LCA within the building sector can play a critical role in improving environmental performance, particularly in reducing GHG emissions. It also facilitates the advancement of sustainable building practices from a life cycle perspective, supporting more informed decision-making among construction professionals and policymakers.

## 9.4 LIMITATIONS AND FUTURE RESEARCH

The assessment of conventional residential buildings within the defined scope, using a mixed-methods approach, was both time-consuming and methodologically challenging. Nevertheless, this approach was essential for collecting empirical data on contextual building design characteristics from a socio-technical perspective involving multiple stakeholders. This enabled the study to strengthen the practical applicability of its findings. However, establishing coherent links between design strategies identified through qualitative methods and those evaluated through LCA posed a significant challenge.

This research examined two case-study buildings and identified green building design strategies, including those aimed at reducing life cycle environmental impacts, while also exploring the applicability of simplified LCA approaches in the building sector. Given the absence of comparable studies with such an integrated and extensive scope in the existing literature, this thesis represents an important starting point for investigating building environmental impacts in Cambodia using an LCA framework. It also highlights how green building strategies and LCA-based decision-support tools can contribute to improved building design practices.

Despite these contributions, a key limitation lies in the integration between the survey of construction professionals and the LCA analysis. While each method has its own inherent limitations, the linkage between these two approaches remains underdeveloped. Future research should focus on strengthening this connection, for example by directly evaluating stakeholder-derived design strategies using LCA or other quantitative assessment methods. In addition, further validation of the identified definitions and characteristics of green building, affordable housing, and green affordable housing would be valuable. This could be achieved through practical applications, such as usability testing in real-world projects or architectural design studios, to assess the effectiveness and influence of these concepts in practice. Similarly, the material recommendations proposed in this study could be further investigated by evaluating

their environmental performance through detailed LCA, thereby strengthening the evidence base for material selection in green affordable housing design.

Future research should also expand the scope of LCA studies to include a wider range of residential and commercial building typologies in Cambodia, ideally through comprehensive cradle-to-grave assessments. While current studies often rely on international or European databases, the development and use of localized databases are strongly recommended. In particular, establishing national environmental impact databases or Environmental Product Declarations (EPDs) for building materials in Cambodia would significantly enhance the accuracy and relevance of LCA studies.

Conducting full LCA studies remains challenging due to limited data availability and a lack of local expertise, particularly in life cycle inventory development and end of life modelling. The inclusion of end of life stages in future studies, especially waste processing (Module C3), is strongly encouraged. This would provide valuable insights into material recyclability and circular economy opportunities, which are particularly relevant for advancing green affordable housing in Cambodia. Further research is also needed to improve comparative analyses between different levels of LCA detail (screening, simplified, and complete). Including additional life cycle modules, such as Module C3 in simplified and complete LCA, and incorporating detailed data on building services would enhance the completeness and robustness of comparisons. This would also strengthen the validation of screening LCA as a reliable tool for early-stage design decision-making. In addition, testing LCA applications using different software tools is recommended to identify more affordable and user-friendly platforms and improve the accuracy and usability of results for practitioners.

Finally, from a long-term perspective, future research should incorporate sensitivity analyses to assess the influence of data quality, methodological choices, tools, and assumptions on LCA results. Expanding the LCA framework to include Life Cycle Costing and Social Life Cycle Assessment is also recommended. Such an integrated approach would enable a more comprehensive evaluation of sustainability by addressing the environmental, economic, and social points of view, and would further support informed decision-making in the Cambodian construction sector.

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# Appendices

The appendices for this manuscript are available at the following shared drive link:

[https://drive.google.com/drive/u/2/folders/18oVM\\_uhOGO7mRVXdr1OxROznzbkmWjgd](https://drive.google.com/drive/u/2/folders/18oVM_uhOGO7mRVXdr1OxROznzbkmWjgd)

The appendices correspond to those cited in the relevant chapters of the manuscript and are organized as follows:

- 1) Appendix A – Interview questionnaire and transcription of semi-structured interviews data
- 2) Appendix B – LCA results in characterized, normalized, and weighted values of the townhouse
- 3) Appendix C – Architectural, structural, and detail drawings of the apartment building
- 4) Appendix D – LCA results in characterized, normalized, and weighted values of the apartment building

