博士論文

Development of a multi-criteria assessment approach for the selection of green building materials integrated into building envelope assemblies: Ranking alternatives for the achievement of the UN Sustainable Development Goals

（建築外皮部材に用いられるグリーン建築材料選定のための
多基準評価アプローチの開発：国連の持続可能な開発目標達成のための建材のランク付け）

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Development of a multi-criteria assessment approach for the selection of green building materials integrated into building envelope assemblies

Ranking alternatives for the achievement of the UN Sustainable Development Goals

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Thesis Supervisor: Professor Takafumi Noguchi Author: Mohamed Omer

Development of a multi-criteria assessment approach for the selection of green building materials integrated into building envelope assemblies

ABSTRACT

Rapid growth in the construction industry has been seen in the last decade due to globalization and urbanization worldwide. The construction sector has the largest impact on the environment, as it has a direct impact on global warming, climate change, energy and water use, and landfill wastes. The building is repeatedly consumed energy and natural resources during it is lifetime; through design, construction, operation, maintenance and demolition. Additionally, buildings are responsible for a large amount of greenhouse gas emissions (GHG) expanded during the building's lifespan. Along the same lines, the growing demand for building materials is unquestionable and it is expected to increase dramatically in the next coming years due to the expected growth of the construction industry and large cities in the coming decades. Hence, this can cause serious environmental and social impacts, and indeed, will increase the need for green building materials for constructing new buildings and infrastructure to accommodate these expansions and to achieve overall sustainable development.

Building materials have a huge impact on the environment during their life cycle from the extraction and transportation of raw materials, to the construction and operation periods until the demolition phase. Moreover, building materials can be a major source of harmful chemical substances which can cause serious health problems. In this regard, a great effort is required to minimize the negative impact of the building and materials on individual health and the environment. A key factor to make building more sustainable than before is to minimize the use of non-renewable sources (materials), harmful emissions, operational cost and energy while increasing the occupant's comfort zone.

Universally, the evaluation and selection of building materials have no universally agreed approach. In the past, basic methods examining a few criteria are often used in the decision-making process of materials selection which guiding to minimal solutions. Hence, one of the most optimal approaches to achieving green building is to select materials that reduce the environmental footprint.

The overall aim of the research is to develop a multi-criteria optimization approach to support architects and designers in the early phases of materials selection where it is

easier to fit the material or service to the appropriate environmental factors than in the later stages. The decision hierarchy for the selection of green building materials has been adapted from published documents such as research papers, manufacturer's specifications, prevident systems (environmental assessment tools), official government publications and reported statistics from the building industry. The research focuses on various aspects related to the building materials properties, environmental assessment tools, sustainable development goals, and building envelope assemblies.

The proposed framework has been linked to the sustainable development goals (SDGs) in order to nationalize the model and to select criteria that cover all aspects of sustainable development. The selection criteria were divided into five main clusters which demonstrated resource and material efficiency, socio-economic performance, health and well-being, water efficiency, and energy efficiency. Then, each of them was assigned to several sub-criteria. The model is meant to estimate the sustainability index for various building materials, either independently or as combined building components (assembly), by giving a score (points) to each module. The new criteria are intended to increase the amount of information existing in the building material industry to support the selection of appropriate green building materials and assemblies and to help in the realization of the 2030 agenda of sustainable development. The object of assessment is the non-structural façade or roof materials (building skins) which could be integrated into building envelope assemblies. Generally, any individual material or composite material whether opaque or transparent, that is intended to be part of a wall system or assembly could be targeted. The framework is designed mainly to be suitable for use in residential and office building types, nonetheless, it could be easily adapted to diverse building typologies to push forward achieving sustainability in the construction industry.

Following the above, the tool and its database were developed using Microsoft Visual Studio 2019. Case studies of a range of individual building materials and assemblies were conducted to provide insights to academics and to show how the proposed framework can be applied in the material selection stage in real construction practice. The findings of this research proved that the proposed model can help decision-makers to assess the sustainability of their material choices, and thus advancing the role of construction materials in achieving the SDGs. Finally, areas for further research are identified.

KEYWORDS: GREEN BUILDING MATERIALS, MULTI-CRITERIA ASSESSMENT APPROACH, DECISION SUPPORT TOOL, SUSTAINABLE DEVELOPMENT GOALS, LIFE CYCLE ANALYSIS, BUILDING ENVELOPE ASSEMBLIES.

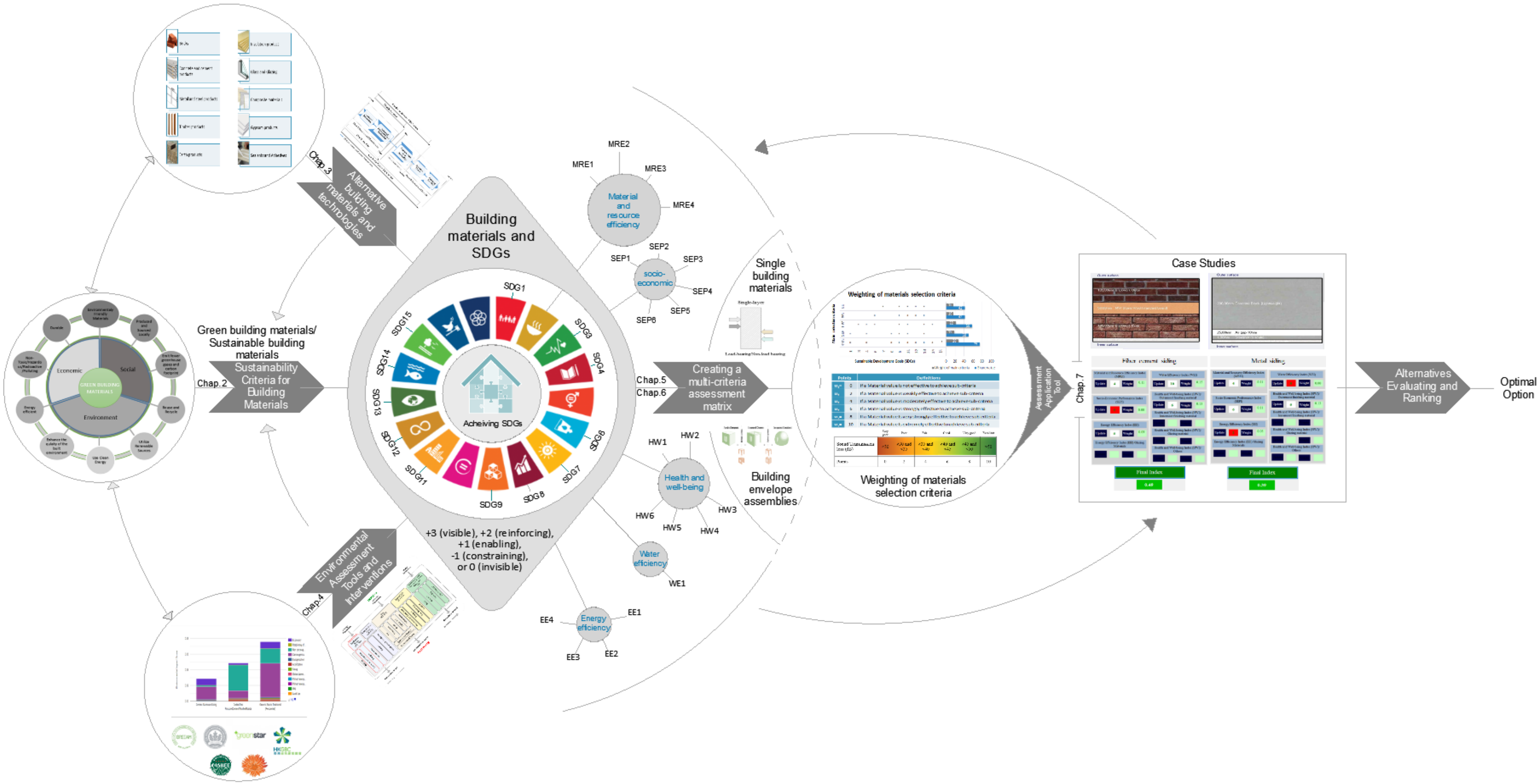

Figure A: Thesis graphical abstract

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LIST OF ACRONYMS AND ABBREVIATIONS

ABBREVIATION	FULL TEXT
EE	Embodied Energy
OE	Operational Energy
VOCs	Volatile Organic Compounds
GHG	Greenhouse Gases
SDGs	Sustainable Development Goals
MCA	Multi-Criteria Approach
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
GBMs	Green Building Materials
LEED	Leadership in Energy and Environmental Design
BEE	Bisagni Environmental Enterprise
IAQ	Indoor Air Quality
FEAHA	Fussy Extended Analytic Hierarchy Approach
WGBC	World Green Building Council
GBRS	Green Building Rating Systems
SBM	Sustainable Building Materials
LCE	Life Cycle Energy
DE	Demolition Energy
CO2-e	Carbon Dioxide Equivalents
EEMs	Energy-Efficient Measures
WWR	Window to Wall Ratio
ABMs	Alternative Building Materials
CCM	Complementary Cementing Materials
WBCSD	World Business Council for Sustainable Development
WHO	World Health Organization
ICSU	International Council for Science
GBCI	Green Building Council Institute
GAs	Genetic Algorithms
AHP	Analytic Hierarchical Process
ANP	Analytic Network Process
GWP	Global Warming Potential

FA	Fly Ash
SCMs	Supplementary Cementitious Materials
BFGS	Blast Furnace Ground Slag
SF	Silica Fume
RCA	Recycled Concrete Aggregate
RMA	Recycled Masonry Aggregate
MRA	Mixed Recycled Aggregate
AWAF	Agricultural Wastes and Aquaculture Farming
RHA	Rice Husk Ash
CCA	Corn Cob Ash
GGBFS	Ground Granulated Blast Furnace Slag
MCM	Metal Composite Materials
CLT	Cross-Laminated Timber
GLT	Glue Laminated Timber
LVL	Laminated Veneer Lumber
MDF	Medium Density Fiberboard
OSB	Oriented Strand Board
DfD	Design For Disassembly
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
SRE	Stabilized Rammed Earth
URE	Unstabilized Rammed Earth
CEB	Compressed Earth Blocks
ODP	Ozone Depletion Potential
EPS	Expanded Polystyrene
XPS	Extruded Polystyrene
PU	Polyurethane
SPF	Sugar Palm Fibre
SPS	Sugar Palm Starch
WPC	Wood-Plastic Composites
WCP	Wood-Cement Composites
OPC	Ordinary Portland Cement
FRP	Fibre-Reinforced Polymer
FRC	Fibre-Reinforced Concrete/Cement Composites

GFRG	Glass Fibre-Reinforced Gypsum
PCMs	Phase Change Materials
BREEAM	Building Research Establishment Environmental Assessment Method
GBCA	Green Building Council of Australia
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
ESGB	Evaluation Standard for Green Building
HK-BEAM	Hong Kong Building Environmental Assessment Method
LBC	Living Building Challenge
EPP	Environmentally Preferable Product
BPDO	Building Product Disclosure and Optimization
EPDs	Environmental Product Declarations
LCCO2	Life Cycle Carbon Emissions
ILFI	International Living Future Institute
NZEB	Net Zero Energy Building
IEQ	Indoor Environmental Quality
MCDM	Multi-criteria Decision Making
ACI	American Concrete Institute
LCC	Life Cycle Cost
HVAC	Heating, Ventilation, and Air-Conditioning
EPA	Environmental Protection Agency
BCA	Building Code of Australia
FRR	Fire Resistant Rating
ECC	Embodied Carbon Coefficient
IEC	Inventory of Energy and Carbon
WRAP	Waste and Resource Action Program
BRE	Building Research Establishment
SR	Solar Reflectance
SRI	Solar Reflectance Index
SAA	Sound Absorption Average
NRC	Noise Reduction Coefficient
STL	Sound Transmission Loss
VT	Visible Transmittance
LCCA	Life Cycle Cost Analysis
SHGC	Solar Heat Gain Coefficient

LIST OF APPENDICES

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis with my work and effort, and this is an original copy of my thesis that has not been submitted to fulfil requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signed……………………………

Omer, Mohamed Ahmed Babiker

September 2021

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DEDICATION

I dedicate this work to my father, Mr Ahmed Babiker, My Mother, Mrs Maryam Hajo, My Wife, Mrs Jihad Ahmed Alian, My Children, My Brother and Sisters and My Entire Family. Thanks for always believing in me and for the encouragement and support you gave me to achieve my desired goal.

PUBLISHED PAPERS

Paper I: **A conceptual framework for understanding the contribution of building materials in the achievement of Sustainable Development Goals (SDGs).**

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Paper-II: **Development of a multi-criteria assessment optimization approach to select façade's materials in correlation with Sustainable Development Goals.**

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Current Status: Under Review

CHAPTER 1: INTRODUCTION

1. CHAPTER ONE: INTRODUCTION

1.1 Introduction

In the last two decades, the use of natural resources was irresponsible and due to that, the world is facing many environmental disasters related to climate change and global warming. Therefore, researchers, policymakers and governments have become more concerned about the effect of these changes in developed as well as developing countries (Shaikh, Nor, Nallagownden, Elamvazuthi, & Ibrahim, 2014). In this regard, buildings have a significant share in the above-mentioned issues (Invidiata, Lavagna, & Ghisi, 2018), they are consuming a massive amount of resources (40% of the natural resources), producing a large volume of emissions (30% during operation phase and 18% during material utilization and transportation), and generating large-scale waste (45-65% of the waste placed to landfills) (Balaras, Droursa, Dascalaki, Hansen, & Petersen, 2003; Castro-Lacouture, Sefair, Flórez, & Medaglia, 2009; Franzoni, 2011; Pulselli, Simoncini, Pulselli, & Bastianoni, 2007; Umar, Khamidi, & Tukur, 2016; Zou, Wagle, & Alam, 2019). This huge percentage has raised concerns over the effect of the buildings in the built environment, and therefore the following question has to be answered:

What are the best sustainable solutions to reduce the negative environmental impacts of the buildings?

Generally, buildings are built to satisfy the needs of different individuals and groups of people, seeing that about 90% of people spend their time in enclosed spaces (Building 2030, 2017). Therefore, the improvement of the building's indoor environment whilst reducing the energy consumption (heating, cooling, and lighting) and CO_2 emissions are highly recommended to provide a healthy and comfortable environment for humans and to achieve sustainability in building (Paulína Šujanová, Monika Rychtáriková, Mayor, & Hyder, 2019; Shaikh, Nor, Nallagownden, Elamvazuthi, & Ibrahim, 2016).

Buildings are using raw materials and energy at every stage throughout their lifecycle starting from the architectural design stage, the structural and materials selection and manufacturing, building construction, usage and maintenance until the demolition and waste recycling stages. For instance, the extraction and processing of raw materials are often entailing extensive use of energy, materials, water and chemicals; and all this turns into pollution. Hence, these impacts can be reduced substantially by creating a multi-criteria assessment tool to be used by the construction stakeholders in every stage starting from the strategic definition of the project up to the in-use stage (Izzet & Tülay, 2014).

Building Materials have the largest impact on the building's energy consumption, as a great volume of raw materials has been used during the construction phase which consumes high energy (Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011). Thus, the embodied energy (EE) of the building materials has a great influence on the total energy consumption besides the operational energy (OE) used for heating, cooling, lighting, ventilation, appliances and equipment. The reduction of energy consumption in the buildings can be achieved through many approaches; for example, using passive design strategies approaches, optimization of building shape, materials and orientation, improving the configuration of the building facades and envelopes, instructing occupant behaviour towards energy use and using renewable energy systems (Harvey, 2009).

Additionally, building materials play a key role in the indoor health environment of the interior zones and occupants well-being. For example, building materials can be a major source of harmful volatile organic compounds (VOCs), these compounds can cause serious health problems associated with paints, adhesives and other materials (Bartzis et al., 2008). According to the data derived from the World Health Institute-WHO (2016b), building materials that contain harmful substances (like asbestos, formaldehyde and lead) have the potential to damage health and causes serious diseases like cancer, lung disease and reduced growth, and could create what is known as a sick building syndrome. Also, they play a major role in improving the thermal, moisture, acoustic, and fire performances of the buildings. However, if they selected well, materials can provide a better indoor environment, fosters resources conservation and help to reduce the environmental implications inextricably linked with the extraction, transportation, manufacturing, installation, reuse, recycling, and disposal of construction and demolition waste.

This research aims to create a multi-criteria optimization approach for the selection of green building materials in the early design stages, in an attempt to establish a starting base-knowledge for policy-makers, designers and developers to achieve long-lasting sustainable development outcomes. The thesis is intended to estimate the environmental impacts of various building materials, as an individual or as assemblies, based on scientifically recognised sustainability indicators.

This introductory chapter defines the research background and identifies the gap in the research and the problem relevance. Moreover, the research purpose, research questions, research aim and objectives, research methodology, and the significance and scope of the study will be outlined in this section. Finally, the research implications and limitations and the structure of the thesis will come at the end.

1.2 Background of the Study

Rapid growth in the construction industry has been seen in the last decade due to the development of globalization and urbanization in the whole world (Z. S. Chen et al., 2019; Govindan, Madan Shankar, & Kannan, 2016). This growth will be coupled with large manufacturing of basic materials and depletion of natural resources and economic advances (Omer & Noguchi, 2020; Ribeiro & Gonçalves, 2019; J. Xu, Deng, Shi, & Huang, 2020). Hence, it is expected to cause continual intense environmental and social impacts, and certainly, rising the demand for balanced solutions to meet the requirements of these growths and to attain global sustainable development (See Figure 1-1).

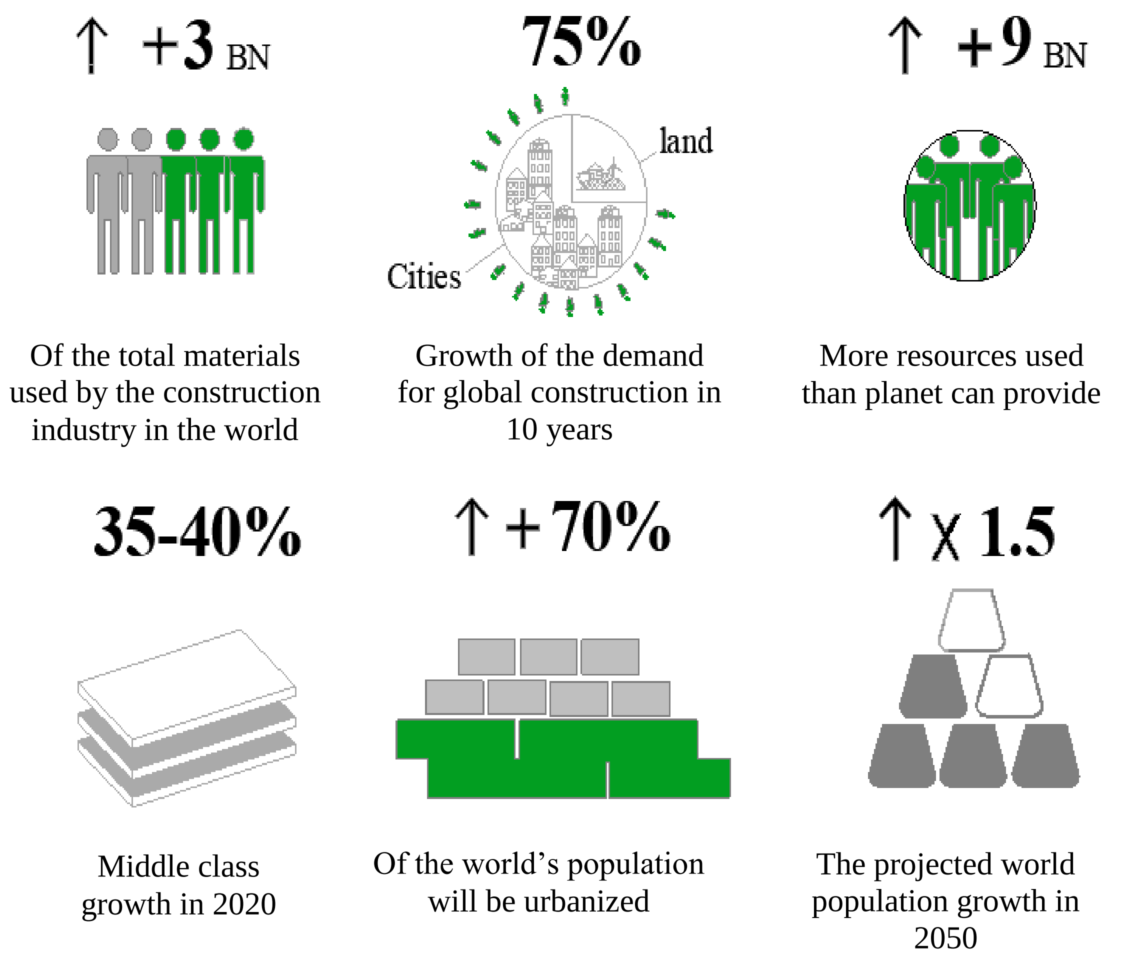


Figure 1-1: The advancement of globalization and urbanization in the whole world

Nevertheless, the fact of the last century proved that modern architecture is not sustainable enough for a long period, and that has been clearly shown in today's buildings. The impact of building on energy consumptions and fossil fuels emissions is unquestionable. Architects and designers are always looking for the aesthetics issues related to the design of the building without realizing the significant impact of the buildings on the built environment. However, by looking at the building process; the construction sector is one of the major consumers of energy and material resources (Peter O. Akadiri, Chinyio, & Olomolaiye, 2012). In response to these impacts, the construction stakeholders became more aware of the environmental damage caused by the building industry, and they started to implement the sustainable objectives at the early design stage for any project. The idea of sustainability is to enhance the quality of life for humans, by granting individuals to inhabit a healthier environment, taking into mind other aspects like economic, social and environmental tasks (Ortiz, Castells, & Sonnemann, 2009).

Sustainable design principles have become part of the official design regulations and policies in many countries. Worldwide, many countries and institutions developed various environmental indexes and assessment tools to monitor the sustainability of the buildings from the initial sketches stage. However, many countries are seeking to apply very restrictive criteria to the building regulations regarding energy efficiency and the impacts of building materials on the total energy used (Vandevyvere & Heynen, 2014). In fact, sustainability is a complex and a wide task, and to design such a sustainable project, many aspects have to be considered: Indoor air quality and noise abatement, CO_2 and GHG emissions, resources and energy efficiency, harmonization with the environment and the integrated and the systemic approaches (Godfaurd John, Clements-Croome, & Jeronimidis, 2005).

On the other hand, to apply sustainability to the building, this task required an agreed decision, clear vision and knowledge from the people participating in the construction of the building including owners, designers, consultants, contractors, suppliers, labours and governors (Zainul Abidin Nazirah, 2010). Undoubtedly, the selection of environmentally responsible building materials is one of the difficult approaches which needs a deep understanding of the multi-functionality of the building materials to reach sustainability.

The selection of building materials is considered one of the most important factors affecting the sustainability of the building (Nassar, Thabet, & Beliveau, 2003). Though selecting unsuitable materials can be costly and it may stop the achievement of sustainable development goals (SDGs) (World Energy Outlook, 2018). Understanding the materials properties and their environmental impacts on the environment are very important to enhance the building's sustainability. Thus, the selection of building materials for their optimal performance and minimal environmental impact is complex as this task required the creation of a multi-criteria optimization approach.

This research will focus on various aspects related to the building materials and sustainability but will concentrate on creating a sustainability index to support the selection of appropriate green building materials and assemblies and to help in the achievement of the UN sustainable development agenda (SDGs). The thesis will go through the studies related to the building materials properties, the environmental assessment tools, building envelope and other environmental aspects. The research will concentrate on the optimization techniques to enhance the selection criteria of the building materials.

1.2.1 The Building Sector Environmental Impact

While they provide uncountable benefits to society and human beings, buildings have a remarkable impact on the health and environment. The building sector is repeatedly consuming a large amount of energy, materials, water, produces a large volume of emissions, and generates large-scale waste (Balaras et al., 2003). See **Table 1-1**.

`Resource	Building Use
Energy	50%
Water	42%
Materials (by Bulk)	50%
Agriculture land loss	48%
Coral reef destruction	50% (indirect)

Table 1-1: The effect of building on the consumption of global resources
Adapted from (Canarslan & Elias-Ozkan, 2007)

According to Zou, Wagle, and Alam (2019), the construction industry occupies 38% of the total energy consumption of the building. The environmental impact of the buildings and construction sector is massive, it accounts for the use of 40% of the natural resources extracted in industrialized countries (Almost 50% of this energy is used for heating and cooling in the buildings), the consumption of 70% of the electrical power and 12% of potable water, and the production of 45-65% of the waste placed to landfills (Castro-Lacouture et al., 2009; Franzoni, 2011; Pulselli et al., 2007). Additionally, they are responsible for a large amount of GHG emissions accounting for 30% used during the operation phase and an additional 18% produced during material utilisation and transportation (Umar et al., 2016).

Universally, the growing demand for energy to serve buildings is unquestionable and it is projected to rise dramatically in the next coming years due to the increase in the world population and economic growth, for example, the population growth percentages projected to reach 9.0 billion in 2035 (Mattoni et al., 2018). Moreover, the construction industry is one of the largest consumers of both renewable and non-renewable resources that exist in nature, it uses a large number of materials during the construction process (S. Ametepey & Anash, 2015). Although the construction phase is relatively short compared to the other building's life stages, it has numerous significant effects on the environment. Hence, the assessment of the impact of the construction sector on the environment might require a 'cradle to grave' perspective (Ofori, Briffett, Gang, & Ranasinghe, 2000). See **Figure 1-2**

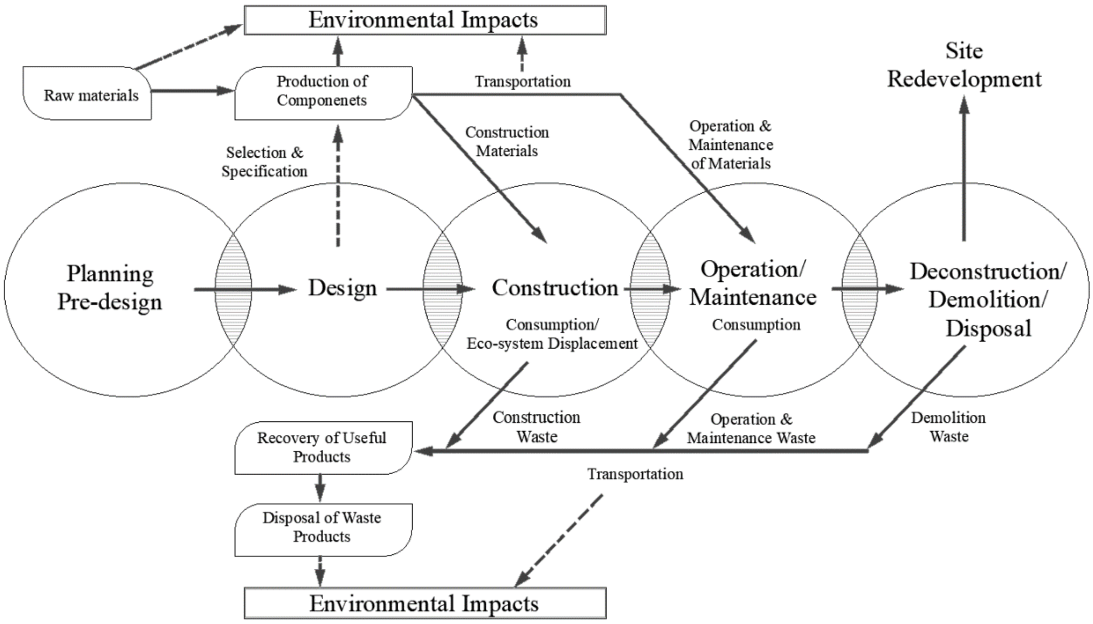


Figure 1-2: Environmental impacts through the Life Cycle of a building construction

Adapted from (Franklin Associates, 1990)

The general trend is to minimize the use of non-renewable sources (including materials), harmful emissions, operational cost and energy while increasing the occupant's comfort zone. In this regard, a great effort is needed to minimize the negative impact of the building on the environment. A key factor to make the building more sustainable than before is by selecting the appropriate materials which allow reducing the negative environmental impacts and life cycle cost of buildings while enhancing the energy performance and the indoor environmental qualities throughout their lifetime.

1.2.2 The Building Materials Environmental Impact

Over the last four decades, the global use of materials almost tripled, from 26.7 billion tonnes in 1970 to 92.1 billion tonnes in 2017, and it is forecasted to grow between 170 and 184 billion tonnes by 2050 (Circle Economy, 2019). In 2019, the world consumed 100.6 billion tonnes of materials of which the built environment consumes 42.4 billion tonnes every year (Circle Economy, 2019). According to Minunno et. al (2021), this figure resembles 60% of the global raw materials consumption. The expected growth in the extraction and processing of raw materials is expected to make adverse environmental impacts and have great significance to climate change.

The construction materials generate millions of tons of waste annually resulting in large carbon dioxide emissions in the built environment. As stated by Yahya and Boussabaine (2010), globally, over 40% of the materials application is operating in the construction of buildings, including non-renewable materials. Building Materials dominate a great share in the total energy consumption of the building during its life-cycle and they are contributing to the total GHG emissions. These greenhouse gas emissions are related to the building's operational energy (OE) as well as the embodied energy (EE) of the building materials.

Building materials consume energy in every stage during their lifetime starting from the extraction of raw materials, manufacturing stage, transportation of materials to the project site, the installation and assembly of building materials, energy used for materials maintenance during building use, and the energy used for demolition and transportation of the materials to the landfill or to recycling site at the end of building lifetime. Previously many studies focus on the reduction of the operational energy of the building because it has the major accountability in the total energy consumption (Pomponi & Moncaster, 2016), but recently the studies found that the embodied energy of building materials could have a significant impact on the total energy used in the buildings during their lifetime (Yung, Lam, & Yu, 2013).

Building materials are responsible for 10%-20% of the building's total energy consumption, from the first instance the percentages look relatively low, but by looking at the development in the production of building materials these numbers will increase steadily in the next coming years (Talakonukula Ramesh, Prakash, & Shukla, 2014; Ruuska & Häkkinen, 2014).

Furthermore, the operational energy demand is challenged by many factors including the design and the shape of the building, the thermal properties of the building envelopes, the size and the efficiency of the equipment and the appliances of the building, and even the user's behaviour. However, with the development in the use of renewable energy technologies and sustainable design approaches, this energy can be reduced significantly and the need for low embodied energy materials will increase reasonably. Moreover, the seeking of the energy-efficient building led researchers and other stakeholders in the construction industry to be more aware of the importance of selecting materials that have low embodied energy and minimum environmental impact in general (Qarout, 2017; Rauf & Crawford, 2013).

Besides, building materials dominate a great share in the total energy consumption of the building during it is life-cycle and they are contributing to the total GHG emissions (J. Hong, Shen, Feng, Lau, & Mao, 2015; Sabnis & Pranesh, 2017; Sagheb, Vafaeihosseini, & Kumar, 2011; Yüksek, 2015). These green gas emissions are related to the building's operational energy (OE) as well as the embodied energy (EE) of the building materials (T. Ramesh, Prakash, & Shukla, 2010; Thormark, 2006). Additionally, building materials have the potential to cause serious diseases and affect the health of manufacturing and construction workers and building occupants (H. S. Park, Ji, & Hong, 2016; Petrović, Vale, Zari, & Petrović, 2017b).

Nowadays, numerous buildings materials are available in the market which makes the selection process even harder than before, because several factors have to be considered to select the most suitable choice. In a typical situation, the consideration of materials properties related to technical, ecological and economic properties are the basic issues to make a successful selection (Wastiels & Wouters, 2012). However, to minimize the impact of the building materials on the environment, the designers need to have a proper multi-criteria selection tool to help them in determining **which is the best building material to satisfy the performance targets?**

1.3 Problem Relevance

Buildings have a huge impact on the environment, and each part of the building has a different effect on this matter. The envelopes (including walls, roofs, floors, windows and doors) are the main elements that affecting the quality of the building; since they separate the building's outdoor environment from the indoor environment (Mirrahimi et al., 2016; Sadineni, Madala, & Boehm, 2011a). They are designed to protect the building from a harsh environment and to provide pleasing thermal comfort for the users. Furthermore, the envelope of the building has a major impact on both EE and OE, and in some cases, the building envelopes can make a contribution of about 48-50% to the total EE of a standard house (Mithraratne & Vale, 2004).

Furthermore, selecting inappropriate materials and assemblies when designing an envelope will affect the people as well as the built environment. If they designated well, the building envelope can lead to a healthier and more sustainable and energy-efficient building. The building materials have to be selected for all construction projects and many factors have to be considered before the final selection decision; which makes the selection process a very complex task influenced by numerous considerations (Ogunkah & Yang, 2012).

In recent years, advanced and sustainable materials have been studied in many kinds of literature and they have seen considerable development (Sadineni et al., 2011a). Presently, building material selection stays constrained to specific performance criteria, and a limited range of properties control the selection process (Wastiels & Wouters, 2009). The traditional methods for the selection of building materials remained two methods: design-oriented and product-oriented and historically the selection of building materials was mostly based on the available data of cost, thermal properties, structural properties and energy implications without taking into consideration the other effective issues (M Kishk et al., 2003). In most cases, the selection of building materials is based on the respective knowledge and experience of the stakeholders, which is most doubtful and ambiguous and frequently guides to poor decisions and impacts building quality (Z. S. Chen et al., 2019). In other contexts, designers apply a few criteria that only fulfil the minimum conditions of the building codes and standards of their countries when selecting building materials and components, thus, these codes do not cover all aspects of sustainability which lead to the selection of materials with minimum performance (Saviz, Luc E, & Saeed, 2020).

Worldwide, many research institutes and organizations have developed various assessment tools[1] to monitor the sustainability of the buildings including the impact of the materials. These tools have been critiqued for the imbalance in the three pillars of sustainability; they examined the environmental subjects with minimum weight on economic or social sustainability (Khoshnava, Rostami, Valipour, Ismail, & Rahmat, 2018; Park, Yoon, & Kim, 2017; Wen, Musa, Onn, Ramesh, Liang, & Wang, 2020). Also, these tools are covering various categories at the same time, with several credits and weights assigned to each building category. The criteria used to examine the sustainability performance of building materials are not limited to the material category which makes the analysis difficult. It is worth noting that, most of the assessment tools have been designated to serve a specific country with regulations and specifications adapted to their

[1] The Building Assessment tools is being developed as a way of supporting the employment of more sustainable practices in the construction industry and building in both developed and developing countries. The tools have a strong emphasis on the aspects of sustainability including social and economic as well as environmental issues. The tools are also aims to develop awareness and support for sustainability among building stakeholders, including designers, clients, building users, facilities managers and project team.

local climate, which means they cannot be applicable when applying to another region (J. Yang & Ogunkah, 2013).

The selection of sustainable materials is a significant strategy in building design and can open new opportunities for a new invention and they can replace the experience of the building materials selection. Nowadays, building materials selection methods could not provide appropriate answers for two main concerns: an assessment based on sustainability principles, and the method of ranking and giving weights to related assessment criteria (O. P. Akadiri, 2011). Accordingly if building materials are to be used optimally, there is a need for consistent and forceful ranking methods based on a multi-criteria analysis approach (MCA) (Maskell, Thomson, & Walker, 2018). Several studies have been made to optimize the performance of the building in different performance criteria including building forms and structure (J. T. Jin & Jeong, 2014), energy (Omrany & Marsono, 2016) and so on. But fewer researches have been done on the selection and the evaluation of the building materials and their assemblies as a whole system using an optimization approach (Flórez, 2010).

Moreover, the evaluation and selection of building materials have brought to the attention of academics, and consequently, several approaches have been conducted to help decision-makers selecting the optimum alternative. Most of the existing studies are focused on the use of Life Cycle Assessment (LCA) methods to evaluate the sustainability of building materials. The LCA-based methods largely focus on the assessment of environmental performance associated with the full life cycle of a material or product from raw material extraction, production, use, replacement and maintenance, and disposal or recycling. Nevertheless, these methodological developments failed utterly in assessing the economic, social and technical performances of building materials as a whole. Also, the processes underlying LCA-based methods are, in many aspects, costly and dependent on the specific application settings as well as the inconsistency of the results (Z. S. Chen et al., 2019).

As a consequence, the multi-objective or multi-criteria decision making (MCDM) approaches have been adopted for materials evaluation and selection to overcome the shortcomings of the previous methods. One limitation of these methods is the limited number of the examined criteria and indicators; which results in incomprehensible decisions concerning the selection and optimization of building materials. Besides, the ranking scale of the adopted criteria has been based on human judgements models (for instance Analytic Hierarchy Process (AHP) or Analytic Network Process (ANP)) which could not characterize the assessment information precisely and guide to minimal solutions. Breaking these limitations or drawbacks makes the main inspiration to investigate the possibility of a novel framework to increase the recent development of green building material selection methods.

Up to date, the consideration of the UN SDGs in the construction industry and particularly in the selection of building materials, their potential realization procedures and the synergies and trade-offs, is barely studied. A gap in the research regarding the selection of building materials still exists; there is no existing framework that enables the comparison between alternative building materials based on recognized environmental assessment criteria to satisfy the needs of architects and designers during the material selection stage. Thus, the challenge of identification of a multi-criteria tool and rating system from a non-conventional strategy based on optimization concept and sustainable approach is highly needed to reduce the negative impacts of buildings and materials on the environment.

1.4 Research Purpose

In the early stage of the building design, typical construction materials are selected and grouped to use in different parts of the building (Materials for walls, roofs, floors, etc.). The goal of architects and other team members participating in the design and the construction process is to find the best materials components which meet their project's needs to successfully reach the project objectives. However, one of the most important tasks to ensure better building performance is by selecting appropriate materials composition. The material's environmental impacts have been considered an important factor to designers and clients, becoming part of the construction and building requirements. Currently, the material selection remains limited to specific performance criteria and a small range of properties.

The thesis will attempt to overcome the gap that exists in real construction practices specifically during the material selection phase. It focuses on optimization techniques to create a multi-criteria tool for selecting building materials. It will cover three main areas which are: building materials and envelope assemblies, the relevant assessment criteria and their acceptable performance, feasible alternatives and sustainability index.

Presently, the need for creating a multi-criteria tool for the selection of building materials to achieve the maximum optimal performance and minimum environmental hazard is highly recommended. However, the purpose of this research is to reduce the negative impact of building materials on human health and the environment by comprehensively evaluating the sustainability of their application against distinguished criteria based on their role in the realization of sustainable development goals of 2030.

1.5 Research Aims and Objectives

The selection of appropriate building materials plays an important role in the achievement of sustainable building (Sustainable Construction) targets throughout the construction process. Although many studies have acknowledged critical factors that affect the selection of sustainable building material, their attention was limited to describe the problem without identifying a clear rational approach that might be useful to decision-makers. Thus, the need for identifying a practical way to facilitate the process of selecting the appropriate building material among a range of options is very required.

The main goal of this research is to develop a systematic method and decision matrix to support and ease the architect and designer’s material selection process. The new approach will be used as a detailed decision support framework for realizing the sustainable development agenda of 2030, at the same time, the approach is designed to be sensible and practical enough to be easily adopted in real construction practice.

The objectives of this research could include variously related issues, but the optimum design and the aim of the research can be achieved through the following objectives (See **Figure 1-3**):

- Investigating the impact of the building materials on the environment through literature reviews and existing case studies.
- Studying different materials and classifying their use by categorizing them into groups (materials for facades and roofs).
- Examining and investigating factors for the material selection to improve the conventional decision methods used in the construction industry.
- Creating a methodological framework for the selection of building materials (Applying diagnosis, prognosis and prescription concepts).
- Exploring the possibility to correlate and examine the framework in real construction practice.
- Certifying and validating the effectiveness of the new optimization tool in the building by applying it to a case study then comparing the overall environmental performance of the case study with a conventional building.

- Reviewing the implications and limitations of the research and identifying the gap for future research.

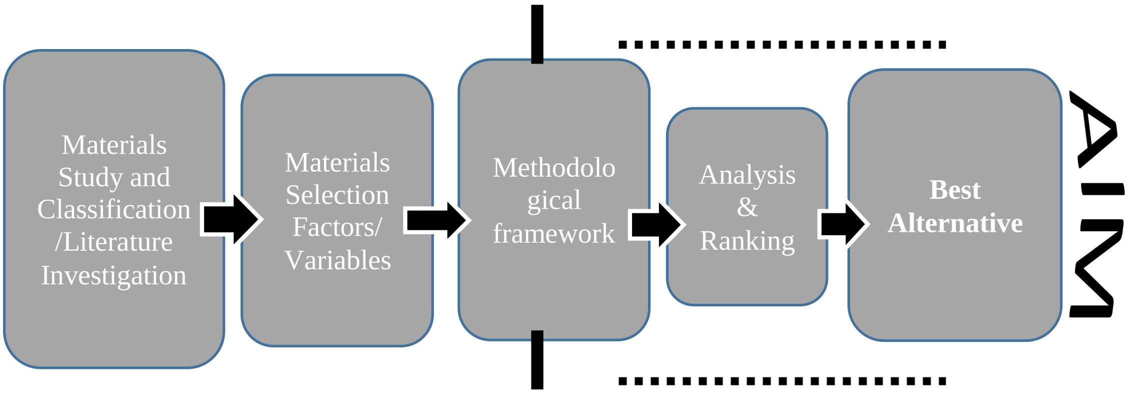


Figure 1-3: Research aim and objectives

1.6 Research Questions

The proposed research will contribute to both the knowledge and the practice level related to building materials selection. The questions have different approaches regarding how they have been reviewed. The questions are proposed to cover four main areas; building materials selection criteria and assessment tools, energy and building materials, building elements and assemblies' concept, and future approaches regarding selection and evaluation of building materials (See **Figure 1-4)**.

However, there are many questions the research is concentrated on, and they are open-ended query questions that require detailed answers:

• What are the most sustainable and durable materials in a specific location and in particular environmental conditions and how to evaluate these materials?

• What are the factors that influenced the selection of building materials?

• How do the Materials act towards the changes of the external climatic Conditions (Reducing the Environmental Impact)?

• How the Building Materials perform to minimize the energy consumption used for heating and cooling in the buildings. (In different climates)?

• What is the best combination of building materials to reduce the negative environmental impacts of the building?

• What materials will we need to use in the future to achieve higher performance and lower environmental impacts?

• What is the best tool for the selection and evaluation of building materials?

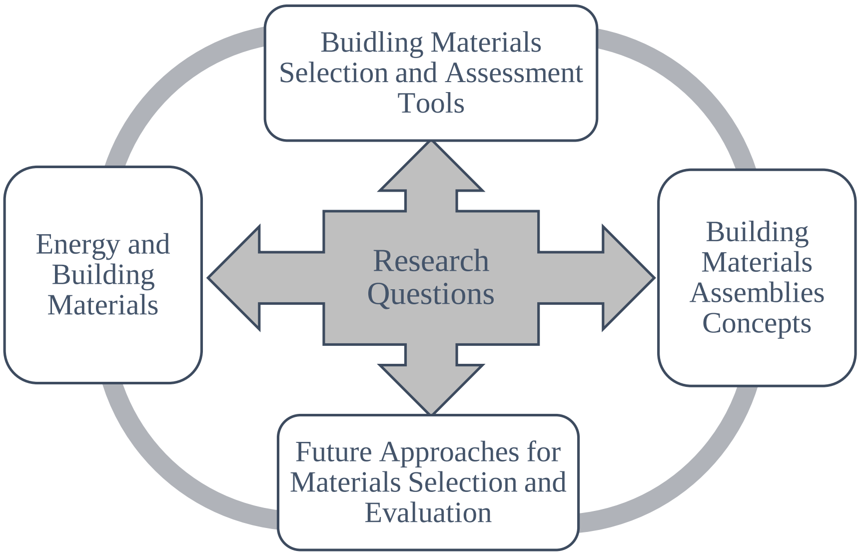


Figure 1-4: Research questions including four main areas

1.7 Significance and scope of the research

This research focused on the development of a multi-criteria optimization tool to enhance the selection methods for building materials. The importance of this study lies in the fact that the selection of building materials stayed controlled with limited performances and few factors and until now designers and architects could not find the appropriate way to make the suitable decision between the large various materials existing in the market, thus, this research gives fundamental answers to related concerns. Part of the novelties of this research is taking into consideration the concept of sustainable development goals (SDGs) in the selection of green building materials.

Furthermore, the study will put more pressure on the building materials industry and manufacturers to disclose information about the environmental performance of their products which will make significant advances for the construction stakeholders to distinguish green from non-green (greenwash) construction materials. It seeks to open several opportunities for the construction stakeholders to discuss the hidden trade-off that normally occurred when checking the sustainability of building materials.

This study will be important for the construction stakeholders including designers, consultants and contractors as well as society and the users of the building. It will make a fundamental change in solving many problems related to the selection of green building materials which generally participate in reducing the negative impact of the building on the environment and enhancing the quality of the indoor environment for users.

Additionally, the findings of this thesis are expected to add astonishing addition to the construction career, researchers and students in the same field and of great benefit to society as it develops new concepts and strategies in the area of building materials and sustainable design.

1.8 Research implications and limitations

The finding of this research is expected to make a change in knowledge of the building environmental assessment tools and the existing methods, and it is expected to improve the decision making for the selection of building materials and assemblies. Accordingly, the first major knowledgeable contribution of the present research is that it provides empirical data for the construction industry regarding the factors and criteria required for selecting the most appropriate building materials. However, it will open the researcher's minds to do more investigation about the importance of materials selection tools and how they can help to increase environmental awareness and to improve the overall sustainability of the buildings.

Alternatively, the output of the research will make changes in construction practices. The research will help in the improvement of the decision making especially for the stakeholders and the decision-makers who participate in the construction process. Furthermore, the developed optimization tool will help in assessing technical, environmental and social issues related to the built environment.

On the other side, few limitations appeared in this research. First, building elements rather than roofs and walls need to be investigated in future work. Secondly, the tool is required to be examined in different climates to know the possibility of integrating it into other regions. The integration of the optimization tool into other architectural design software is another limitation in this research that needs more future studies.

1.9 Research method in brief

This research involves three consequent stages:

1) Identifying the influencing criteria that affecting the selection of green building materials through examining the link between building materials, sustainability, and sustainable development goals. This step followed by an extensive literature search concerning the investigation of the ongoing practices and prior study in the field of environmental impact assessment and material evaluation, examine the role of the existing rating systems in material evaluation, and overview the traditional and advanced building materials and technologies used in the construction industry and examine their sustainability features. Five main criteria involving environmental, socio-economic,

health and wellbeing, energy and water aspects, as well as a variety of sub-criteria (as indicators), where possible, have been taken into consideration.

2) Creating a multi-criteria assessment matrix (decision tool) for evaluating the sustainability index of single building materials and building envelope assemblies and converting the matrix into an assessment application tool by using visual basic programming in visual studio 2019. The criteria have been weighted based on their role in the achievement of sustainable development goals (SDGs) of 2030.

3) Studying and validating the model (tool) by applying it to assess the sustainability index of several building materials and building façade assembly for a residential-detached house in Tokyo-Japan to aid decision-makers in the selection of green alternatives. In this phase, the entry Data have been collected through interviews and questionnaire surveys distributed to building material manufacturers. The questionnaire was to identify the value of each product in the implemented criteria.

1.10 Thesis structure outline

The thesis starts as normal by naming the title of the research on the title page, then the abstract, list of figures, list of tables, list of abbreviations, list of appendices, author's declaration, acknowledgement, dedication and published papers. The thesis is divided into eight chapters showed in Figure 1-5 and within each chapter, there are main and sub-headings used to organize the structure of the thesis. In the end, the references and appendices are added as well as the applicant's curriculum vitae. However, the specific details can be described as below:

Chapter One: Introduction

This chapter gives a general introduction to the thesis. It starts by introducing the title of the thesis and then identifying the research background and identifying the existing problem and gaps. The research purpose as well as the research questions, research aims and objectives are also identified in this chapter. Furthermore, the significance and the scope of the research are presented besides the research implications and limitations. In the final part of this chapter, the research methodology in brief and the structural outline of the whole thesis is discussed in detail showing the contents of each chapter and the interrelationship between them.

Chapter Two: Building Materials, Sustainability and Energy Efficiency

In this chapter, the relevant literature is reviewed to acknowledge the gap in the research area and also to know the previous studies which have been done in the same research field. This chapter builds a theoretical base for the thesis. It is divided into small sub-titles to cover all the data related to the research area. The link between building materials and sustainability has been studied in the first part, then the building materials and energy performance in the next part. The criteria and the factors used in previous research for the selection of building materials as well as the interlinkages between building materials and sustainable development goals are also discussed. Finally, the optimization concepts related to building materials and energy efficiency have been intensely investigated.

Chapter Three: Conventional and Advanced Building Materials and Technologies

This chapter intended to give a general understanding of the commonly used building materials for facades, their feasible consideration and environmental impacts, as well as their sustainable alternatives. Peer-reviewed studies are analysed to show the new advanced technologies, strategies and methods which could be utilized to increase the performance and functionality of conventional building materials and to make them more adaptive, healthier and environmentally friendly. It is aimed to assist architects and designers to identify and trace the most recent sustainable building materials and technologies applied in the construction industry and provide some basic information on the life cycle of these alternatives.

Chapter Four: Building Environmental Assessment Tools

In this chapter, the most recognized and accessible environmental assessment tools have been identified, classified, and summarized in order to increase transparency and thereby help practitioners and decision-makers to understand the similarities and differences of the tools' components and how they assess the building. These tools include leadership in energy and environmental design (LEED), building research establishment environmental assessment method (BREEAM), comprehensive assessment system for built environment efficiency (CASBEE), building environmental assessment method (BEAM PLUS), green star of the green building council of Australia (GBCA), and living building challenge (LBC). A detailed and systematic comparison of these tools was performed along with their information accessibility and global recognition. The analysis of the material criteria and weights embedded in each tool was identified, classified, and summarized separately to highlight the importance of these issues.

Chapter Five: Development of a Conceptual Framework for the Assessment and Selection of Building Materials

This chapter aims to define detailed and comprehensive criteria for the selection of green building materials based on scientifically recognized indicators and measures. The chapter starts by identifying the material selection criteria (main and sub-criteria) and linked them with sustainable development goals (SDGs). The weight of the main criteria was determined based on their role in the achievement of sustainable development goals and a point ranking system was developed to demonstrate the importance of the main criteria and sub-criteria and to harmonize the units of each sub-criteria. Also, a minimum acceptable range of the sub-criteria was identified to ensure that the least green-oriented requirements could be reached when selecting façade materials. Afterwards, a sustainability index and weighting attributes have been developed to rank material options for building projects.

Chapter Six: Review of Building Envelope Assemblies and Materials

The integration of green materials into building roofs and facades came out in this chapter. The chapter starts by identifying the importance of building envelopes in tolerating water (moisture), sound, heat, fire, and pollution, and also identifying their ability to provide security, safety, thermal and visual comfort. More detailed and comprehensive criteria for selecting building envelopes and assemblies have been discussed in this chapter. The chapter highlights the importance of including all aspects that are important for decision making and for achieving sustainability in building. The chapter identifies the limit values for each criterion, which, if not exceeded, determines the fulfilment of the requirement for given useful properties.

Chapter Seven: Case Studies

This chapter consists of case studies of a range of individual building materials and assemblies in an attempt to show how the proposed tool presented in the prior chapters can be applied in the material selection stage in real construction practice. It is proposed to ensure that the relevant research questions and hypotheses are explored through a variety of perspectives allowing for multiple facets of the research problem to be revealed and understood and also formulating an argument to support the overall conclusion. Nevertheless, further analysis and discussions will be shown in this chapter.

Chapter Eight: Conclusions and Recommendations for Future Work

In this last chapter, the general conclusion, summary and recommendations of the work have been discussed. The concluding remarks have been made by looking at the achieved results and what was exist in reality. Nevertheless, the benefits and drawbacks of future work have been expressed in this chapter.

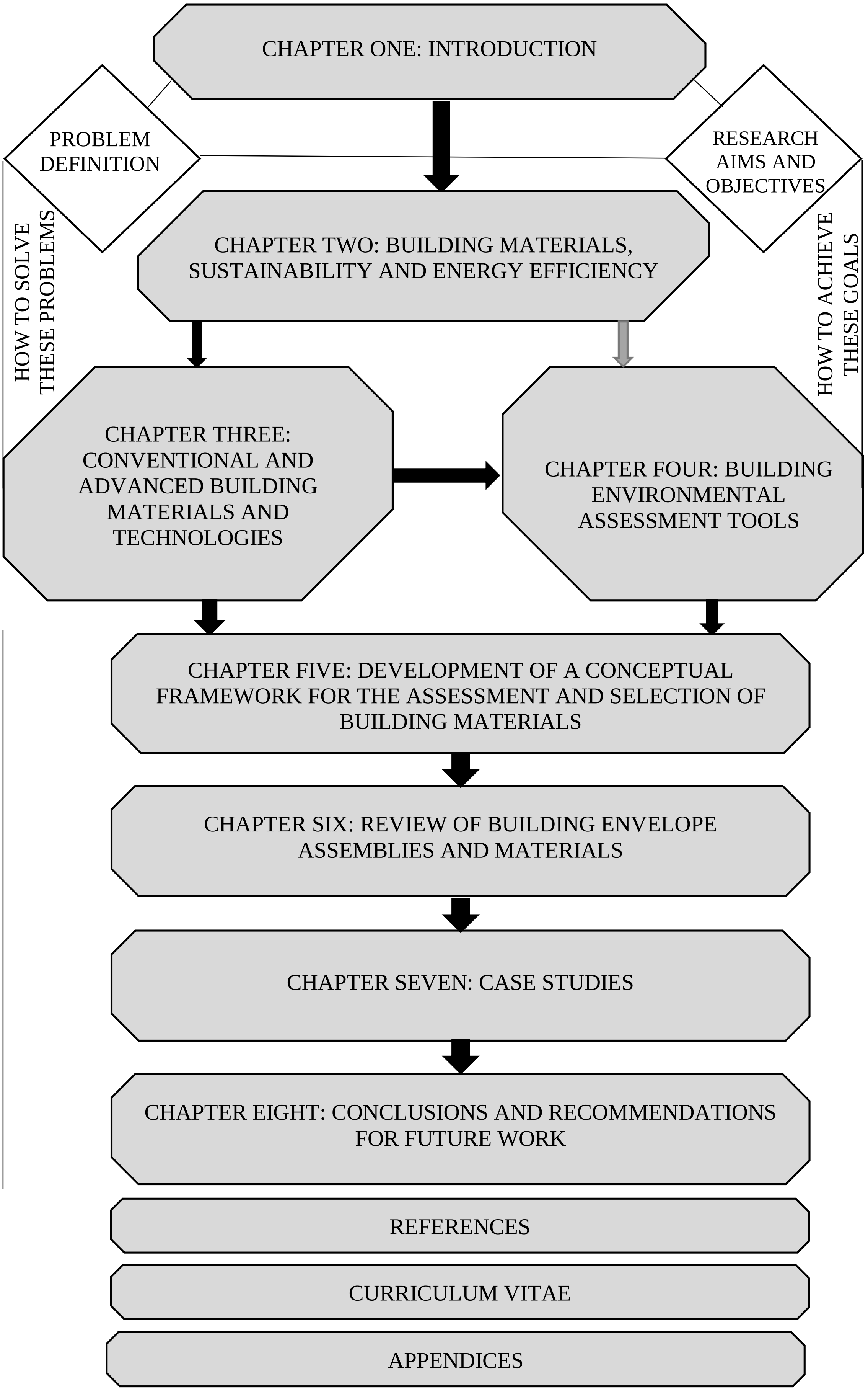


Figure 1-5: Thesis structure outline

CHAPTER 2: BUILDING MATERIALS, SUSTAINABILITY AND ENERGY EFFICIENCY

2. CHAPTER TWO: BUILDING MATERIALS, SUSTAINABILITY AND ENERGY EFFICIENCY

2.1 Building Materials and Sustainability

Building material can be defined as any material which is used for construction purposes, it can be naturally arising in nature such as clay, sand, wood and rocks or it can be artificially made by human beings (synthetic materials) such as brick, insulation, concrete, metal, plastics and so on (Kubba, 2017). Materials have been considered an essential element for building construction as far back as 400 BC (Tuflite, 2016). The first building materials were biodegradable and nondurable (for example; Leaves and animal hides). Afterwards, with the industrial revolution followed by the development of machinery and large-scale industrial production, many innovative materials have been discovered for building construction (such as Metals and Concrete). Moreover, with the continuing research; various construction materials have been available in the market to satisfy the need of creating modern architectural designs. Nevertheless, the evolution in the materials industry has been accompanying by many environmental problems related to climate change and global warming. Building materials have been becoming part of the sustainable development concept which is becoming an important task within the construction industry aiming to reduce the negative impact of the building on the environment (Martins & Gonçalves, 2012).

The concept of sustainable development has been introduced in a report by the world commission on environment and development in 1987 as *"meeting the needs of the present without compromising the ability of future generations to meet their own needs"* (Brundtland, 1987). However, since that time many studies and strategies have been developed all around the world to apply this concept in many fields. In 1992 at the united nations conference on environment and development held in Rio de Janeiro, the agenda of sustainable development have been formulated and three sustainability pillars have been introduced; economic development, social equity and environmental protection. See **Figure 2-1**

Recently, there is still confusion and conflict among researchers about the proper definition of sustainable development, but they have a common agreement that; sustainability must meet social, economic and environmental goals (KOLTUN, 2010). Moreover, the United Nations announced 17 Sustainable Development Goals (SDGs) in

2015 by including quality education and good health, no poverty and zero hunger, clean energy and economic growth, sustainable communities and cities, responsible production and consumption, climate action and life on land (United Nation-UN, 2015). Thus, buildings and construction materials can contribute directly to meeting the SDGs and defeating the conventional practices related to the construction of the building.

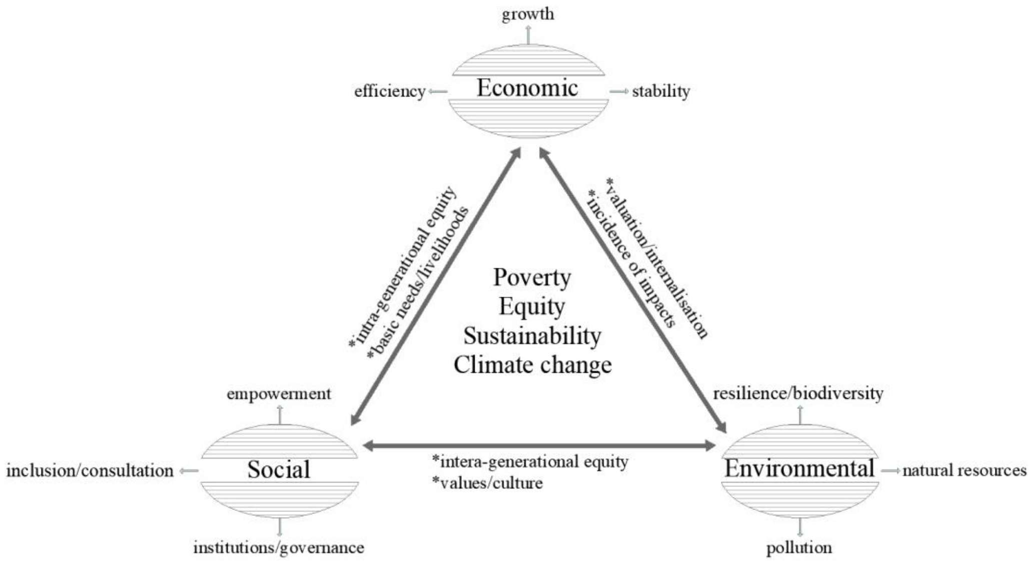


Figure 2-1: Sustainable development and sustainability pillars

The above figure shows a Sustainable Development Triangle- Key Elements and Interconnections Adapted from (Munasinghe, 2007)

Also, other Controversy and debates existed between researchers in the definition of the exact meaning of Sustainable Building. Various definitions have been used by different authors and organizations in different fields (Glavič & Lukman, 2007). However, According to Kibert (2012), a sustainable building is *“the practice of creating and using healthier and more resource-efficient models of construction, renovation, operation, maintenance and demolition”*. Additionally, Kibert (2012) defined green buildings as *“Healthy services and facilities which aimed to use an efficient resource approach and ecological based concepts during the design and construction of the building*”. As stated by Glavinich (2008), the green building is defined as *“A building that offers the specific requirements for the building performance while reducing the interruption and improving the performance of local, regional and global eco-systems during and after the construction process and identified service life ”*.

Recently, the term“ high-performance buildings” has been used as equivalent to “green buildings”, however, according to a report from Congressional Research Service (2017), energy savings in buildings and industry, Definitions, "*A high-performance building is a building which can be integrated and optimized on a life cycle base all major performance features, including energy-saving and environment, safety and security, durability and sustainability, accessibility and functionality, cost-benefit, productivity and other operational considerations*".

Buildings have the capability to make a significant contribution to a more sustainable planet for humankind. But the question: ***What makes buildings green?*** Doesn't get the right answer up to date. The greenness of the building is often referred to as being an environmentally friendly or sustainable building, which needs the incorporation of various strategies during the design and construction stage. The green building indicates the quality of the building products using the principles of sustainability, as defined by Sheth (2016), the green building is a high-performance building, which consumes less energy and water, produces less waste, sustains the indoor environment for it is users, and uses efficient building materials. However, the words "green" and "sustainable" are often used interchangeably in the research, but they have different meanings. The word "green" focuses on people and products, while the "sustainable" phrase is a wider term that investigates the impact of these products during their lifetime to minimize their negative impact on human health and the environment (Kates, 2010). The "green" term has been dealt with the harmful characteristics of the building materials and how to eradicate them to ensure the greenness of the products.

Materials play an essential role in the overall performance of the building in achieving a more sustainable design. However, with the current development in the construction industry and infrastructure, the need for creating eco-friendly, zero-energy and energy-efficient buildings is increasing every day (Karakoç, 2017). This makes materials selection an important task in the field of architecture and construction. However, according to the data derived from the international energy agency, the demand for basic materials such as steel, cement, plastic, paper and aluminium will increase dramatically and may reach double the existing levels in 2050 (Allwood, Cullen, & Milford, 2010), which prove the need for sustainable development for building materials.

On the other hand, many advantages can be achieved by applying green buildings approaches, the construction of greener buildings can contribute to the reduction of 50% of water consumption, 30% of energy consumption, 80% in waste generation and they can provide a healthier environment for the users (Kasai & Jabbour, 2014). Green buildings help to improve biodiversity and protect the eco-systems, saving the operational energy and the maintenance cost and improve health and thermal comfort for the human (Zuo & Zhao, 2014). Oppositely, applying sustainable design ideas in real construction practice, is a very difficult task, as various sustainability issues interrelated to each other. Furthermore, there are shared common objectives among researchers regarding the environmental and sustainable design issues which include but not limited to: minimizing the energy consumption, using sustainable building materials and products, optimization of operational and maintenance performs and providing a healthy indoor environment for the building's occupants. In the same manner, the above-mentioned goals have been existing in some building sustainability assessment approaches to determine the sustainability level in buildings (Bragança, Mateus, & Koukkari, 2010; Geissdoerfer, Savaget, Bocken, & Hultink, 2017).

Construction specialists are becoming more aware of the environmental suitability of the building materials and they started to pay attention to the damage and the impact of their usage. There are growing concerns among construction stakeholders to arise new strategies to reach the best environmental performance of their projects, therefore, the first step of integrating sustainable design ideas in the building is by the selection of materials that have minimum environmental hazards.

2.1.1 Sustainable (Green) VS non-sustainable (non-green) building materials

The interrelationship between the building and it is components is frequently unnoticed in traditional construction practices (Canarslan & Elias-Ozkan, 2007). The existing practices proved that buildings negatively impact the environment by consuming a large number of materials, energy and waste during the construction phase and after the completion of the building. Hence, the future trend is to use materials and energy wisely without harming the environment. Many studies have been conducted to distinguish between sustainable and non-sustainable building materials or as defined previously, between Green and Non-green building materials. In general, any material which affects negatively on human and environment, and destructive the nature during it is life cycle can be considered as a non-green building material.

Moreover, Spiegel and Meadows asked a question: "***When Are Green Building Materials Not Green?***" The question claimed that designers must identify green building materials which are really not green and they have to look beyond the characteristics of the materials to its manufacture. However, the term "greenwash" or "greenwashing" has been appeared in the construction industry to show that many companies purport to green their products and materials without any proof (Spiegel & Meadows, 2010). As stated by Sam Kubba (2010) it has become a challenge to verify the validity and reliability of environmentally preferable materials. However, deep research of green building materials and a critical evaluation based on recognized testing procedures need to be considered before selecting "green products". Even though there is no commonly agreed definition for the term sustainable or green building materials, many researchers came up with different explanations. However, due to the unclear definition of sustainable building material, many materials have been introduced in the construction market as green or sustainable materials without any evidence of their suitability.

The term green building material (GBM) has been mentioned intensively in the literature; as defined by Kubba and Sheth (2010): the ideal building materials are environmentally friendly materials that would have no negative impact rather than having a positive impact on the environment. Patil et al. (2017) defined sustainable building materials as materials produced or sourced locally and they have an outstanding performance in terms of identified criteria. Sandanasamy, Govindarajane, and Sundararajan (2011) Stated that sustainable building materials are materials that emit fewer greenhouse gases and carbon footprint and can be reused and recycled. According to Umar et al. (2016), sustainable building materials are *"materials that are produced and sourced locally, they can be reused, they utilize renewable sources, they use less energy, and they emit lower harmful emissions (CO_2 and GHG)"*. Spiegel and Meadows (2010) defined green building materials as environmentally responsible materials which respect the limitation of non-renewable resources, act with nature's cycle and ecosystems, non-toxic, recycled and recyclable, energy and water efficient, and can enhance the quality of the indoor environment.

Another explanation has been stated by Susanto and Lubis (2018) as Building materials with natural components have higher sustainability merits and more green features than the other materials with non-natural material content. A further study prepared by Huberman and Pearlmutter (2008), concluded that: Sustainable building materials: use renewable energy in the production process, use local resources, they are reusable and recyclable, integrate industrial, consumer and recycle wastes, reduce the Co_2 emissions, they are energy efficient materials and they can enhance the quality of the built environment. Additionally, Cai and Sun (2014) studied the current situation of application of green building materials in China, and they stated that; Green building materials are ecological, healthy and environmentally friendly materials, they use clean energy during production, harness less energy and natural resources, they are non-hazardous, non-polluting, and non-radioactive as well as offering a healthy environment for a human. Moreover, it has been noticed that the energy efficiency of building materials is being continually addressed in all previous definitions as an important factor affecting the greenness of the materials. From this standpoint, the development and integration of energy-efficient materials and technologies in buildings to enhance energy consumption are extremely demanded.

In conclusion, we can say that: green building materials are mainly renewable materials or materials which can be reused and recycled and they have a low negative environmental impact throughout their life cycle, they are durable, they use less energy than conventional materials and they can offer a decent indoor environment for the building's occupants (**Figure 2-2**). Studies have proved that applying green technologies in green building can increase the efficiency of the building by up to ten times in terms of resource utilization (Macaluso, 2010). The advancement in selecting green building materials is extremely important to our civilization to achieve more energy saving, materials and environmental conservation.

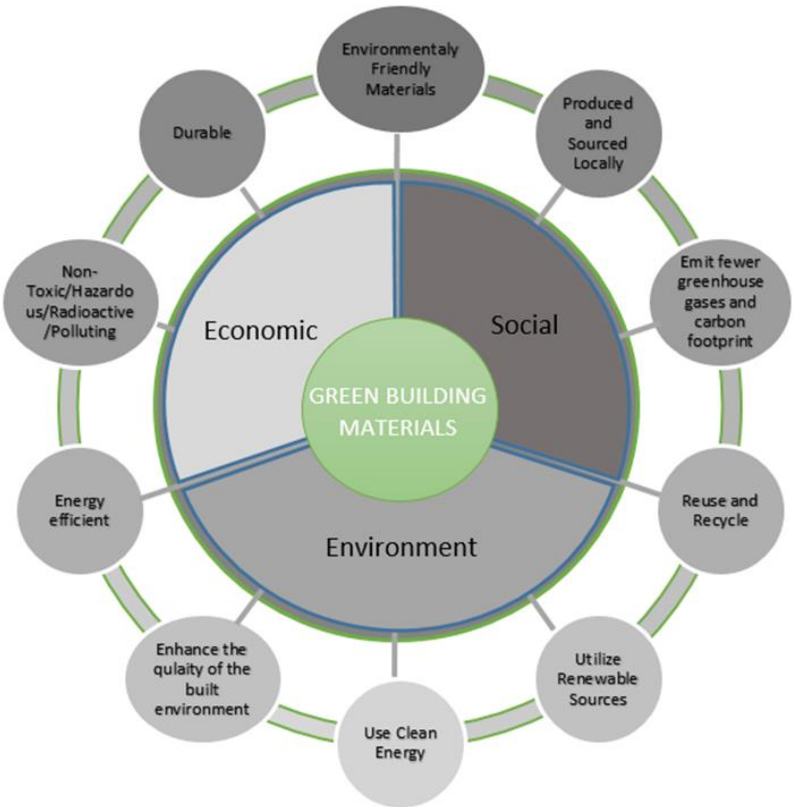


Figure 2-2: Definitions of green building materials

2.1.2 Barriers Affecting the Selection of Sustainable Building Materials

It has been agreed that Building materials play an essential role in achieving a more sustainable design. The use of sustainable approaches and sustainable building materials (SBM) faces a lot of challenges in the construction practices and many facts have been subjective against developing green buildings. However, various barriers have been mention in previous studies, for example, the lack of knowledge, awareness and expertise for the designers and construction practitioners regarding building sustainable development (M. Kang & Guerin, 2009; Williams & Dair, 2007), the initial and the ongoing cost of the SBM (Samari, Godrati, Esmaeilifar, Olfat, & Shafiei, 2013; Williams & Dair, 2007), lack of demand and supply (Griffin, Knowles, Theodoropoulos, & Allen, 2010; Samari et al., 2013), the lack of building codes and regulations in real construction practices (Abisuga, A O; Oyekanmi, 2014; Landman, 1999), and the perception of extra time needed to apply SBM during the construction process (Chan & Kumaraswamy, 2001). However, the above-mentioned factors bound the ability of building design to use sustainable design ideas and to apply sustainable building materials in the construction process, respectively. This suggests the need for more initiatives and practices guides to improve the application of sustainability in buildings.

Likewise, many previous studies have been investigating the barriers affecting the application of green design ideas in buildings in various developed and developing countries. Samari et.al (2013) examined fifteen barriers that may affect the development of the green building in Malaysia and listed: the lack of credit resources to cover up the front cost, the risk of investment and the shortage of demand in addition to the higher final price as main barriers.

In another research, O. Ametepey, Aigbavboa, and Ansah (2015) studied the Barriers affecting the sustainable construction industry in Ghana and he concluded that the five brightest barriers to the implementation of sustainable construction are classified as fear of culture change, lack of governmental obligation, fear of higher investment costs, the absence of professional knowledge, and lack of regulation. Correspondingly, Peter O Akadiri (2015) has reviewed thirteen different barriers affecting the selection of sustainable building materials in three completed projects (case studies) in Nigeria. He figured out that, the perception of having a higher cost, and the lack of sustainable materials information are the most ordinary barriers affecting the selection and the use of sustainable building materials in Nigeria.

Furthermore, Williams and Dair (2007) investigated five completed projects to analyze the barriers which hinder the progress of sustainability objectives in England. The research explored the experience of construction stakeholders regarding the barriers participating in stopping the sustainable building in the country, the research investigated twelve different barriers and it concluded that the lack of concern for sustainability measures and information, the overall cost as well as the insufficient expertise and lack of powers are the main barriers stop the achievement of sustainably in buildings. Nguyen, Skitmore, Gray, Zhang, and Olanipekun (2017) examined thirty-three barriers affecting the acceptance of green building in Vietnam and the finding of the research concluded that social and awareness, economic and cost, governmental and institutional barriers and technical and knowledge constraints are the main four factors preventing green building implementation.

Moreover, Hakkinen and Belloni (2011) studied barriers and drivers for sustainable buildings and they claimed that sustainable building does not hold back because of the lack of information and assessment methods, but because of the difficulty of implementing new methods. The research investigated nine barriers and the results outlined the most important actions to promote sustainable design as the development of a system to awareness clients about the importance of sustainable buildings, the step-up of new approaches and requirements for sustainable building management, utilization of sustainable building managing tools, improving the competition between designers and the working team, and development of new concepts and facilities. Alsanad (2015) investigated the level of awareness of sustainable and green practices among construction stakeholders in Kuwait and the results showed that the lack of knowledge and awareness was found to be the main barriers barring the use of sustainable construction approaches in Kuwait.

Additionally, Saleh and Alalouch (2015) reviewed the current challenges stand in front of the application of sustainability in the construction industry in Oman which concludes the lack of availability of green building materials and tools, the effectiveness of the cost, lack of knowledge and awareness, projects interruptions, and the lack of environmental regulation. The researchers recommended that the lack of well-defined sustainable construction practices is the most significant factor affecting the implementation of sustainable Construction practices in Oman. Wimala, Akmalah, and Sururi (2016) handled research to identify the barriers to the green building movement in Indonesia from the viewpoint of building occupants. The research identified ten barriers and the findings show that the inadequate understanding of the green building concept from the occupants and some stakeholders is the main barrier hindering the progress of the green building. Other barriers including the implementation of the green concept are demanding, lack of supported environments, resistance to change, insufficient knowledge and information, negligence of green building practices, high cost of green building choices, lack of supervision and awareness, low available green products on the market, and lack of building management role are also participating on the issue.

Lastly but not least, more barriers have been included in the literature, including the uncertainty in the efficiency and the quality of the final product (Landman, 1999), lack of motivations (Changing the conventional methods) (Marker, Mason, & Morrow, 2014; P. B. P. Rao & Pavan, 2013), lack of wide-ranging tools to compare materials choices (AlWaer & Kirk, 2012; Ikediashi, Ogunlana, Oladokun, & Adewuyi, 2012). However, in some studies the barriers have been classified and identified on groups depends on five measures; economic concern, technological issues, societal challenges, professional challenges and policy concern (M. S. Saleh & Alalouch, 2015). Further, Bon and Hutchinson (2000) classified economic concerns as a serious challenge to achieving sustainability in construction, besides policy concerns and technical issues. See **Figure 2-3**

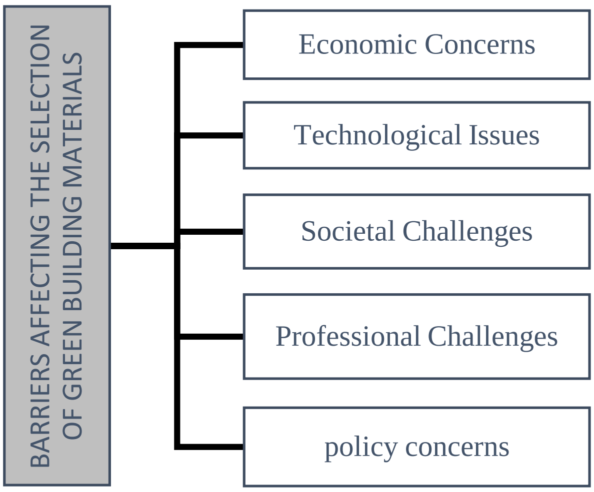


Figure 2-3: Barriers affecting the selection of GBM

The Above figure has been originated from Saleh and Alalouch (2015) and Bon and Hutchinson (2000)

To conclude this part, there have been extensive studies on the barriers affecting the implementation of sustainable design approaches (including the GBM) in buildings, these researches have been conducted in both developed and developing countries, indicating the importance of the research as a global issue. However, there is a common similarity in some barriers revealed from the existing body of knowledge including the lack of knowledge and awareness, lack of availability of green building materials and tools, the overall cost, time constraint and lack of legislation and sustainable building codes. See **Table 2-1**

CODE	AGREED BARRIERS	CODE	OTHER BARRIERS
B1	lack of knowledge and awareness Regarding sustainable material selection information and practices	B1	Uncertainty in the durability and quality of green building materials and the final product
B2	lack of demand and supply	B2	Lack of government support and incentives
B3	Lack of availability of green materials and tools	B3	**Lack of wide-ranging tools to compare and evaluate materials choices**
B4	The initial and ongoing cost	B4	Lack of strategy to promote green building materials
B5	Time Constraint	B5	Lack of expertise and professional knowledge
B6	Lack of Legislation and Building Codes	B6	Resistance to change traditional construction processes
		B7	Low flexibility for alternatives or substitutes

Table 2-1: Barriers affecting the selection of sustainable building materials

2.1.3 Sustainability Criteria for Building Materials

The evaluation of building materials starts by generating criteria for the selection of environmentally friendly materials. The criteria should approve the overall environmental performance goals of the projects. The challenges there exist when dealing with different types of buildings whether a building is a new or renovated building (Froeschle, 1999). From the definitions of green building materials, many characters can be obtained from literature reviews and the criteria should have a wide range to deal with different kinds of projects. Conversely, materials should reveal certain characteristics in order to be called sustainable or green materials, yet, so far many studies have been investigated the selection factors and the functional requirements of the GBM. In the Green Building Materials ’96 conference (1998), many characteristics had been introduced to define the term “green building materials”, which include:

I. An environmental performance check-up is necessary for the ingredients of building materials.

II. A life cycle assessment of the building materials should be considered to determine the environmental impact of the materials.

III. No permanent environmental pollution should occur during the production and demolition phases.

IV. Materials should not be integrated into components that cannot be disassembled.

V. The material should be energy efficient during the production and operation of it is used.

VI. A third-party guarantee for some products is needed.

VII. It is possible to dismantle after building use.

Moreover, some studies categorized the selection of sustainable building materials depending on four pillars: environmental performance, economic performance, building performance and material characteristics (Karakoç, 2017). Yuxin Zhang (2012), created a comprehensive rating method to help architects in selecting building materials to improve the building performance in the long term. The new method has been originated by combining two of the existing green material methods (LEED AND BEE). The thesis categorized the selection criteria into four sections and measure the weight of each section, the main factors included: environmental performance, economic performance, building performance and material credits.

Windapo and Ogunsanmi (2014) examined the building materials in construction in Nigeria and proposed sustainability indicators that can be used to measure the environmental impact of the building materials. These indicators include embodied energy (EE), Carbon Dioxide emissions, source sustainability and five indicators based on previous research studies. See **Figure 2-4**

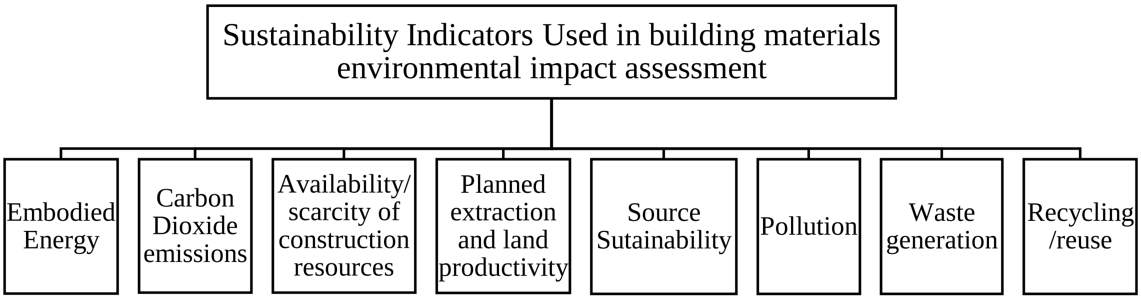


Figure 2-4: Sustainability indicators for selecting green building materials

Adapted from (Windapo & Ogunsanmi, 2014)

In previous studies, Augenbroe and Pearce (1998) created a framework of indicators to be used in sustainable construction. The research detailed four main requirements that can be used to measure the sustainability of building materials including environmental performance, technical performance, resource use performance and socio-economic performance. Moreover, sub-indicators have been categorized under the main indicators. A detailed description can be shown in **Table 2-2**.

Environmental Performance	**Technical Performance**	**Resource use Performance**	**Socio-economic Performance**
Impacts on air quality. ▪ Carbon Dioxide ▪ Hydrocarbons Impact on water quality. Impact on ozone depletion potential. Site Disturbance. Assimilability. Scarceness. Processing Impacts.	Durability. Service Life. Maintenance. Serviceability. Code compliance. R-Value. Strength. Constructability.	Energy. ▪ Embodied ▪ Operational ▪ Efficiency ▪ Distributional ▪ The degree of Processing. Source Reduction Materials ▪ Renewable ▪ Recycle/Recyclability ▪ Reuse/Reusability ▪ Renewability ▪ Local/ transport distance ▪ Packaging Requirements	Occupant health/indoor environment quality ▪ VOC outgassing ▪ Toxicity ▪ Susceptibility to biocontamination Appropriate for ▪ Scale ▪ Climate ▪ Culture ▪ Cite Economics ▪ Contribution to economic development ▪ Cost ▪ Labour skill requirement ▪ Labour amount requirements

Table 2-2: Sustainable Building Materials-Sample information Requirements

Adapted from (Augenbroe & Pearce, 1998)

Lynn Froeschle (1999), created environmental assessment criteria to evaluate the green building materials and their specifications. The matrix used a rating system and points to compare similar materials which satisfy the most appropriate application of the projects. The study ordered the environmental assessment of GBM into three levels: research, evaluation and selection. The research is the most time-consuming aspect of the three-part process; evaluation is dependent on the product information provided by manufacturers which affect directly in the final environmental scores and selection of the alternatives. Nonetheless, the environmental assessment matrix has been used as a reference in many studies, the matrix composed of sixteen characters including low toxicity, minimal emissions, low volatile organic compounds (VOC) Assembly, recycle content, resource-efficient, recyclable materials, reusable components, sustainable sources, durable materials, moisture resistant, energy-efficient, improved indoor air quality (IAQ), water-conserving, healthful maintenance, local product and affordable material. See **Figure 2-5**

Environmental Criteria	Prod. "A"	Prod. "B"	Prod. "C"
Low Toxicity			
Minimal Emissions			
Low-VOC Assembly			
Recycled Content			
Resource Efficient			
Recyclable Materials			
Reusable Components			
Sustainable Sources			
Durable Materials			
Moisture Resistant			
Energy Efficient			
Improved IAQ			
Water Conserving			
Healthful Maintenance			
Local Product			
Affordable Material			
Environmental Score:			

Figure 2-5: Environmental materials assessment matrix

Adapted from Froeschle (1999)

Moreover, Hoang, Kinney, and Corsi (2009) described certain criteria for green building materials, such as low toxicity, recyclability, durability, minimal chemical emissions, and they often contain reused and bio-based substances. Also, Ogunkah and Yang (2012) identified a framework of factors for assessing the sustainability of building materials, they presented six main factors including; site factors, environmental and health factors, sensorial factors, economic factors, socio-cultural factors and technical factors. Additionally, Khoshnava, Rostami, Valipour, Ismail, and Rahmat (2018), Created a multi-criteria decision method to characterize the green building materials aligned with sustainability pillars by identifying four main criteria of the GBM including resource efficiency, indoor air quality, energy efficiency, water efficiency and affordability. Then, some 23 detailed criteria have been identified within each of the main criteria. However, the findings of the research stated that affordability is one of the notable criteria in the selection procedure of GBM while resource efficiency and embodied energy arrived in the second and third place respectively. See **Figure 2-6**

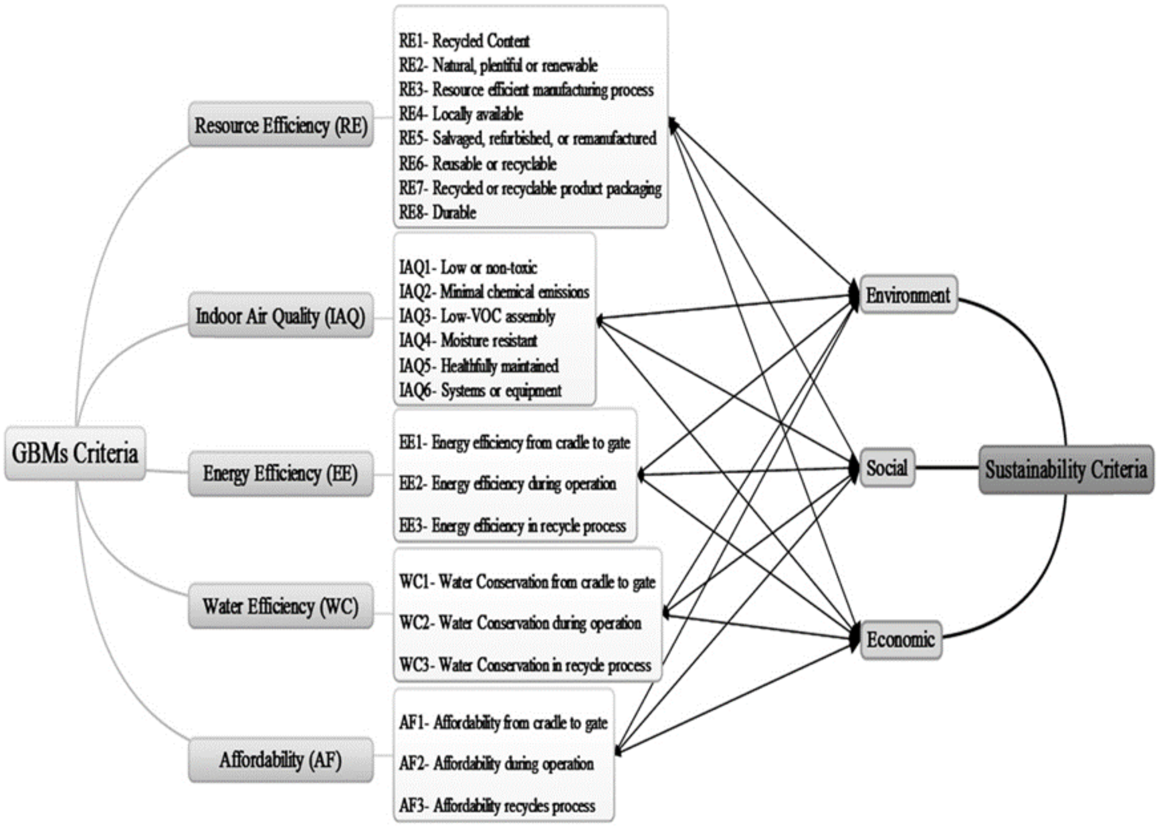


Figure 2-6: Green Building Materials and Sustainability Criteria

The above prototype and basic model adapted from (Khoshnava et al., 2018)

Govindan et al. (2016) introduced a model to evaluate and select preferred sustainable materials through a hybrid multi-criteria decision-making Approach. The model classified the criteria of building materials using sustainability pillars: economic, environment and society, and other sub-criteria indicators have been linked to the three pillars to select possible alternatives materials. The results showed that environmental values followed by social sustainability were more highly considered than economics, which is usually in conflict with environmental affairs.

Additionally, Akadiri and Olomolaiye (2013) described a set of criteria using a fussy extended analytic hierarchy approach (FEAHP) to evaluate building materials base on their sustainability. Three proposed roofing materials have been investigated in a case study. The model intended to help design team participants in the selection of SBM for a building project, and three sustainable assessment criteria were used including environmental (11 criteria), technical (6 criteria) and socio-economic(7 criteria) for building material selection. Then, The twenty-four criteria have been compacted into six assessment factors including environmental impact, life cycle cost, resource efficiency, performance capability, social benefit and waste minimization. The findings of the research proposed that the fuzzy perception problem of building materials selection required comprehensive and practical criteria. **Figure 2-7** illustrates the hierarchy of the decision making adapted from (Peter O. Akadiri et al., 2013).

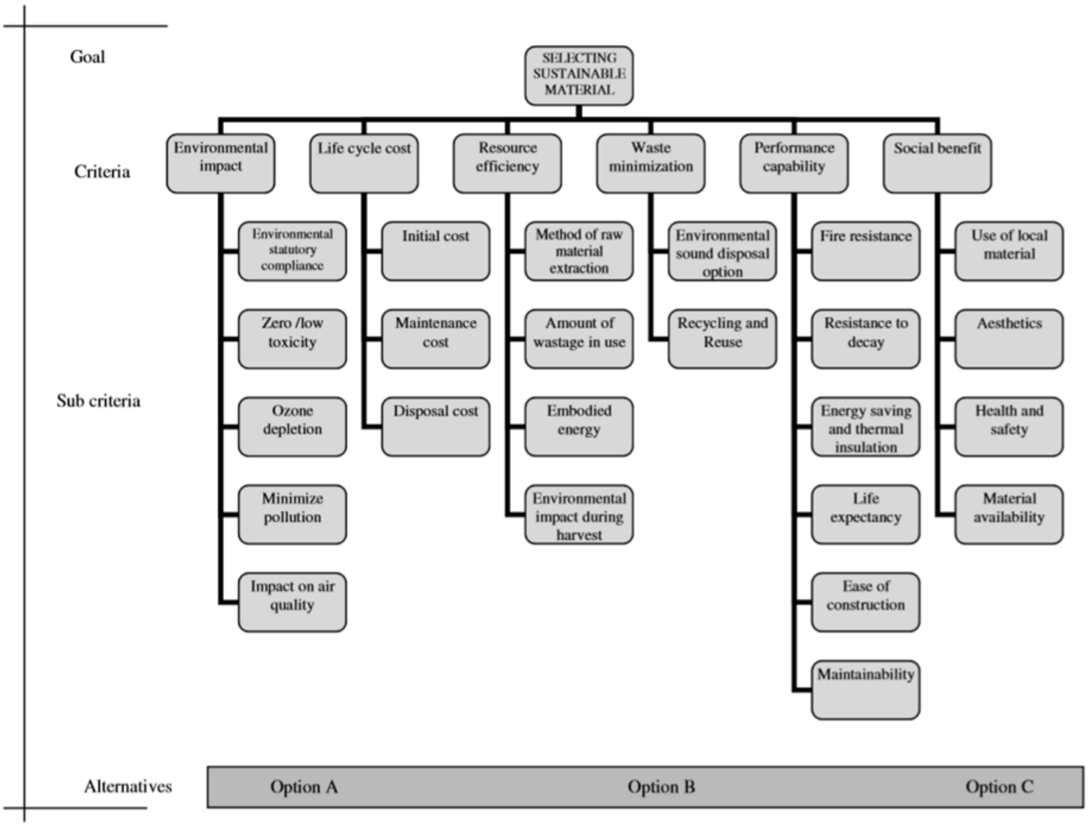


Figure 2-7: Selecting Sustainable Material Criteria

Mahmoudkelaye, Taghizade Azari, Pourvaziri, and Asadian (2018) proposed a model to select sustainable construction materials for exterior enclosure in a residential building in Tehran-Iran. The materials selection main criteria were sectioned into main four sets comprising economic, technical, environmental and socio-cultural criteria. Moreover, the four criteria have been separated into sub and subsidiary criteria and three materials have been investigated in this research including brick and mortar wall, cedar siding and Aluminum cladding. The findings of the research proved that the aluminium siding is the best sustainable material for the proposed case study following by brick and mortar and cedar siding respectively.

On the other hand, there are several green councils worldwide supporting the green buildings market through the implementation of sustainable criteria and rating systems.

There are two currently used methods for green material selection; the green building rating systems (GBRS) and the life cycle assessment and life cycle inventory. They are classifying and rating the materials and buildings depend on their environmental impacts to save the environment, enhancing energy efficiency and users well-being with minimum focus on the social and economic aspects of sustainability. Moreover, the World Green Building Council (WGBC) which grouping approximately eighty national green building councils, is working to transform the conventional practices of building construction into a more green and sustainable approach. There are many Green Building Rating Systems (GBRS) to assist construction stakeholders in identifying design criteria and evaluating the sustainability of the materials and buildings in general (Rahardjati, Mohd Faris, & Arazi, 2011). However, detailed insights about these rating systems and their effectiveness have been presented in chapter four.

2.1.4 Overlapping between sustainability criteria

The complexity level in selecting green building materials is higher than that of the selection of conventional ones. This is attributable to the big number of participated stakeholders as well as due to the required balance between the environmental, economic and social factors of sustainability. The trade-off between the sustainability criteria is inescapable due to their interdisciplinary nature (R. F. de Magalhães, Danilevicz, & Palazzo, 2019). However, understanding the acceptable level of performance (the lowest value or minimum requirement) for each criterion as well as how they could be measured and achieved in a balanced way is essential for achieving sustainability in construction projects. Achieving a win-win approach in which the trade-off between two conflicting criteria could be managed systematically is better than having a win-lose policy in which one criterion is fully achieved and the other is neglected. In most cases, the trade-off between the criteria compromising environmental and economic objectives are taken into consideration because they could achieve a remarkable impact in advancing a balanced sustainable development (Ali-Toudert & Ji, 2017).

Some studies recommended guidelines for the management of the criteria trade-offs in the early design stage. For instance, Morrison-Saunders and Pope (2013) developed a framework for understanding and managing the trade-offs by the distinction between acceptable and negotiable facets of the criteria. The study recommended that critical limits for each of the categories (criteria) need to be identified and assessed to determine their acceptability level. In the same line of thought, R. F. de Magalhães et al. (2019)

created a tool composed of a set of 13 guidelines stand on a recommendation in literature from sustainability projects to control the trade-offs in the decision-making process. The guidelines have been categorized into three clusters including the early decisions, acceptable and negotiable aspects, and the decision process support**. Table 2-3** shows the guidelines required for the management of trade-offs.

Group 1 Early decisions	**Group 2** Acceptable and negotiable aspects	**Group 3** Decision process support
• The primary objective of project sustainability should be privileged. • Before interventions, the suitability potential of the project in the scenario must be assessed to reduce the existence of complex trade-offs. • The sustainability trade-offs management of a project must occur systematically and not individually. • Between two incompatible objectives, the one which does not transfer potential negative impacts to the future should be prioritized. • The early decisions should consider the views of different actors involved in the process.	• Unacceptable aspects of the sustainability project should be defined, and the degree of flexibility to changes for these aspects should be established. • The offsets should be defined - project aspects that are considered negotiable, among the unacceptable ones. • The alternatives selection for the project should be carried out within the established limits for acceptable and negotiable sustainability aspects.	• It is mandatory to comply with the minimum requirements of standards and legislation. • All decisions should be aligned with the organization's strategic objectives. • Decisions on project trade-offs should be guided by the expected results defined in the pre-development stages. • Decisions must be based on minimizing or accommodating process variability, which can scarcely be eliminated. • The sustainable product's adequate performance should be prioritized, even when it is detrimental to the adoption of solutions with lower environmental impact.

Table 2-3*:* Guidelines to control trade-offs between criteria for sustainability projects

Adapted from (R. F. de Magalhães et al., 2019)

2.1.5 Life-Cycle Assessment and Life-Cycle Inventory

Life-Cycle Assessment (LCA) is a multi-step method to evaluate the environmental qualities and prospective impacts associated with a building material or product throughout its entire lifetime (cradle-to-grave). Life-Cycle Inventory (LCI), on the other hand, is a process of counting resources and emissions (inputs and outputs) for the entire life cycle of a product, process, or activity, thus, it is one of the most essential phases of an LCA. The calculation could be established from raw material extraction and processing, manufacture, operation, maintenance and repair, demolition, disposal, and recycling. See **Figure 2-8**

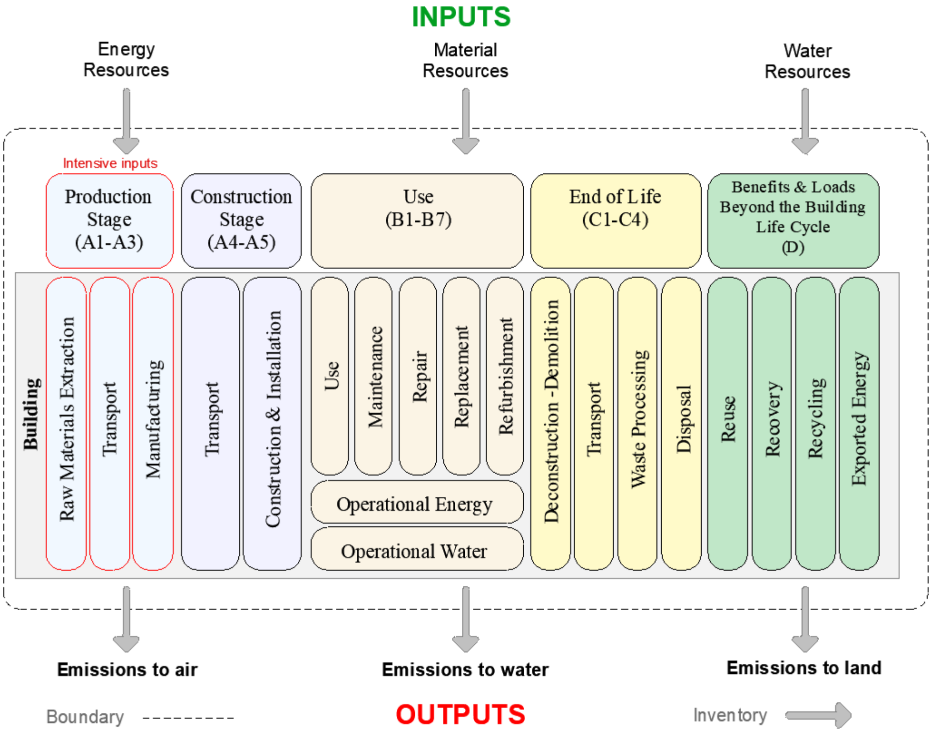


Figure 2-8: Life Cycle Assessment Application Framework for Building Materials

On the material level, the LCA measures the energy, carbon and other atmospheric emissions, waterborne releases, solid wastes, etc. However, life cycle assessment tools and life cycle inventory can assist construction stakeholders to realize the long–term environmental performance of building's products. There are several available tools such as SimaPro, GaBi, BEES, openLCA, Umberto, Athena IE, GREET and many others which could be used for this purpose. See **Table 2-3**

Life Cycle Assessment Tools	Origin of Use
Athena IE	North America
BEES	US
AusLCI	Australia
CMLCA	Europe
Ecoinvent	Europe
ELCD	Europe
GaBi	Germany, the US, Europe
GREET	US
Inventory of Carbon and Energy	UK
Korean LCI	Korea
Okobaudat	Germany
SimaPro	Europe, Australia
Tally	US, Europe
US LCI	US

Table 2-4: The most commonly used Life Cycle Assessment Tools

The Above Table Originated from (Azari & Abbasabadi, 2018a)

GaBi and SimaPro[2] are the most common and dominant tools which have been used to assess the environmental impact of various products and buildings in different parts of the world (Azari & Abbasabadi, 2018a; Herrmann & Moltesen, 2015). Generally, energy and emissions are the most common topics emerging in literature for SimaPro and Gabi. Both tools combine a user interface for modelling and product systems and many life cycle assessment databases (Herrmann & Moltesen, 2015). SimaPro includes many life cycle impact databases such as EcoInvent, ELCD, LCAfood, ETH-ESU, US LCI, and IVAM while GaBi holds several databases for instance GaBi professional and EcoInvent. However, there are limitations of using these tools in design and construction practices; they required expensive licenses and a high level of knowledge to operate (time-consuming) (Sinha, Lennartsson, & Frostell, 2016); and inconsistencies of Life Cycle Assessment results are observed because most the applied data are based on European average values (Lopes Silva et al., 2019). Furthermore, in Canada and the United states the Athena Eco calculator and Athena impact estimator (developed by Athena institute) are the most commonly used software to calculate the environmental impacts of buildings and components. The tools are particularly helpful when comparing the baseline scheme with other alternatives. They can generate a report on several LCA measures include Energy Consumption, Fossil Fuel consumption, Acidification Potential, Global Warming Potential, Human Health particulate, Ozone Depletion Potential, Smog Potential, and Eutrophication Potential (An example is illustrated in Appendix A). In general, the majority of LCA tools are not transparent and comprising pre-defined building materials and assemblies that have already been assessed previously, hence, the users are confined to them and they cannot adjust them or create their customized products.

On the other hand, the BEES (Building for Environmental and Economic Sustainability) created by (NIST) National Institute of Standards and Technology Building and Fire Research Laboratory is one of the common tools that apply LCI (Lippiatt, Greig, & Lavappa, 2010). The tool can be used to measure the environmental and economic performance of building products all through their life stages (see Appendix A). The life cycle impact assessment (environmental performance) is based on the ISO 14040 series of standards, while the life cycle costing is measured using the ASTM standard life-cycle cost method. Although it contains around 230 building products, the selection of green

[2] Simapro Developed by the Centre of Environmental Science of Leiden University (CML), released in 1990 and distributed by PRé Consultants in the Netherlands. Likewise, Gabi is firstly launched in 1992 by a German company (PE INTERNATIONAL).

materials is yet restricted. The based products cannot be adjusted or customized and products from outside cannot be selected and compared.

2.2 Building Materials and Energy efficiency

Energy consumption is one of the most important environmental issues in today's world. The development of energy resources is a crucial factor for the economic development of any country and has become an essential element of the developed communities. In the industrialized world, energy resources have been widely used in transportation, industry, agriculture, communications, agriculture and in many other fields. This produced energy releases harmful gases (GHG) which are the main cause of global warming. Nevertheless, promoting energy saving while reducing energy and harmful emissions are major strategies in sustainable design (O. P. Akadiri, 2011).

Energy efficiency is concerned with saving energy, and the percentage of energy use and production, while material efficiency is about the careful use of natural material resources, effective management of supplies, reduction of waste, and recycling of materials (Ruuska & Häkkinen, 2014). Although the energy consumption of buildings varies globally according to many factors such as climate, geographical location, cultural habits and social differences, it is estimated that buildings construction and operations are responsible for 36% of global final energy and accounted for 39% of energy-related carbon dioxide emissions in 2019, in particular, 11% of this emissions are caused by the manufacturing of building materials and products (IEA, 2019). (See **Figure 2-9**).

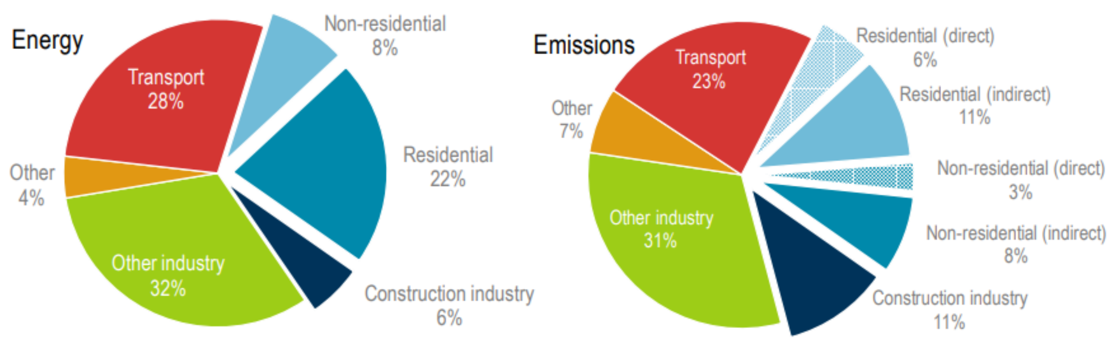


Figure 2-9: Global share of buildings and construction final energy and emissions, 2018

Adapted from (IEA, 2019)

Building Materials, belonging to over 2000 types of products and materials, commonly classified into two groups: metal materials and non-metal materials. The metal groups including steel, Aluminium, copper, etc., and the non-metal composed of stone, cement, ceramic and others (Song et al., 2018). It should be noted that about 40 per cent of the total materials are consumed in the construction industry and this amount is expected to rapidly increase in the future (Asif, Muneer, & Kelley, 2007). Building materials have a huge impact on the environment during their life cycle from the extraction and transportation of raw materials to the construction and operation periods until the demolition phase. However, these processes involve the consumption of a massive amount of energy.

Buildings use energy during their life period, these include Operational Energy (OE) and Embodied Energy (EE). As stated earlier in chapter one, the OE requirements of a building can be described as the energy used to operate the buildings to maintain the indoor environments and day-to-day maintenance of the buildings, including energy used for the HVAC system (heating, ventilation and Air-conditioning,), lighting, hot water use and so on (T. Ramesh et al., 2010).

Various studies showed that OE has a huge percentage of the building's total energy consumption. As stated by Thormark (2006), the OE accounts for 85-95% of the total energy consumed in buildings, however, many strategies have been initiated to minimize the energy consumption caused by OE through the using of passive design strategies, enhancing the insulation of the building envelopes and using of other technical solutions. The OE in the building's lifetime can be expressed by the following formula:

$\mathbf{OE = E_{OA}L_b}$ ……………………………(1) Adapted from (T. Ramesh et al., 2010)

where OE = operating energy in the lifespan of the building; E_{OA} = annual operating energy; L_b = lifespan of the building.

On the other hand, the embodied energy (EE) can be defined as the energy consumed during the construction phase of the building including the energy used during the excavation and manufacturing of the materials, energy consumed for transportation of materials to the site, energy used at the time of construction and renovation of the building. As stated by Ramesh et.al (2010), the EE can be divided into two parts: the first part is the initial embodied energy incurred in the early stage of building construction

$\mathbf{EE_i = \sum m_i M_i + E_c}$ ……………………….(2) Adapted from (T. Ramesh et al., 2010)

where EEi = initial embodied energy of the building; mi = quantity of building material;

Mi = energy content of material per unit quantity; Ec = energy used at the site for erection/construction of the building.

The second is the recurring embodied energy which is the energy used in the rehabilitation and maintenance of the building. (T. Ramesh et al., 2010)

EEr = ∑miMi[(Lb/Lmi) − 1] ……….…… (3) Adapted from (T. Ramesh et al., 2010)

where EEr = recurring embodied energy of the building; Lb = lifespan of the building; Lmi = lifespan of the material (i).

The total energy of the building during its is lifetime composed of several enters from operational and embodied energy during the manufacturing phase, operation stage and destruction phase. See **Figure 2-10**

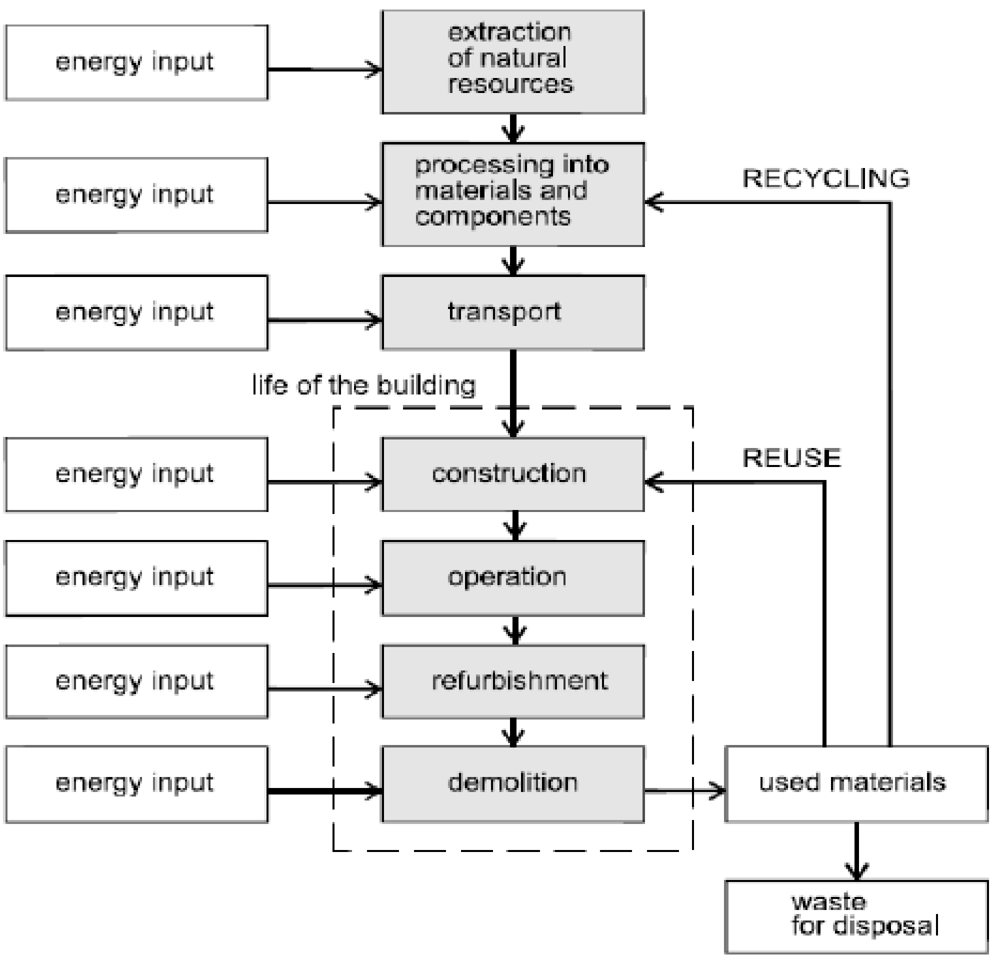


Figure 2-10: Life cycle energy stages of building

Adapted from Crowther (1999)

The method of assessing lifetime building energy is known as life-cycle energy analysis. Therefore, the life cycle energy of the building is the total of the overall energies consumed in its life cycle.

LCE = EE + OE + DE……………………………………….…………………….(4)

Where LCE = Life Cycle Energy, EE = Embodied energy, OE= Operational Energy, DE= Demolition Energy.

2.2.1 Construction Materials-Embodied Energy and GHG emissions

Embodied energy (EE) and greenhouse gases (GHG) are the main serious indicators in the impact evaluation of buildings in the environment. Whilst EE is consumed during the initial design stages of building construction, the OE grows over the building lifetime. Generally, the use of higher EE leads to higher GHG emissions and higher global warming (Sabnis & Pranesh, 2017). Thus, EE plays an essential role in the assessment of the sustainability of the buildings, as stated by Alcorn and Baird (1996), EE embodies all the energy consumed during the materials excavation and extraction, manufacturing, transportation and deconstruction stage. However, from the definition of EE, it can be clearly seen that four energy categories are needed to determine the material's EE including energy consumed in the production of material, energy used for transportation of material from and to the site of the building, energy used for the construction of building materials, and lastly energy used for the demolition of building materials. Every construction material fixed in the building consumes energy in its manufacturing and transportation to the building.

In previous studies, many types of embodied energy have been identified during various stages of a building's lifespan such as; direct and indirect energy, initial energy, recurrent energy, demolition energy and operating energy. For example, Fay, Treloar, and Iyer-Rangia (2000) defined direct energy as the energy purchased by the contractors and sub-contractors onsite and off-site to assist any construction work, prefabrication, administration and transport movements under their rule while indirect energy is the only embodied energy of the building materials.

According to the Energy briefing sheet on the embodied energy and carbon, issued by the Institute of Civil engineers ICE (2015), the embodied energy can be classified into three groups. Firstly, the initial EE often referred to as primary energy, which includes the energy used for the abstraction and manufacture of the materials in addition to their transportation and assembly on-site, thus, initial EE is all energy used before the building is occupied. Secondly, recurring energy is refereeing to the energy required to maintain and renovate the building during it is lifespan. The third is the demolition energy necessary to dismantle and dispose of the building at the end of its life, and it is difficult to obtain due to the uncertainties regarding the future of the building and the construction industry.

Moreover, three common systems have been used to compare different products/Materials: cradle-to-gate, cradle-to-site and cradle-to-grave. The cradle-to-grave system is used to examine the embodied energy and embodied carbon of building, and it is calculated the energy used during raw material extraction, refining, production, transportation, maintaining until the demolition and the disposal of the materials at the end of the building lifetime. A cradle-to-gate method looks at the energy consumed during the extraction of the raw materials, through to the manufacturing of the product within the factory, until the finished product is ready to deliver outside the factory. The third approach is a cradle-to-site; is very similar to a cradle-to-gate system in which the energy required to transport the materials from the factory to the project site is added to the total energy used in the cradle-to-gate system (Tingley & Davison, 2011). See **Figure 2-11.**

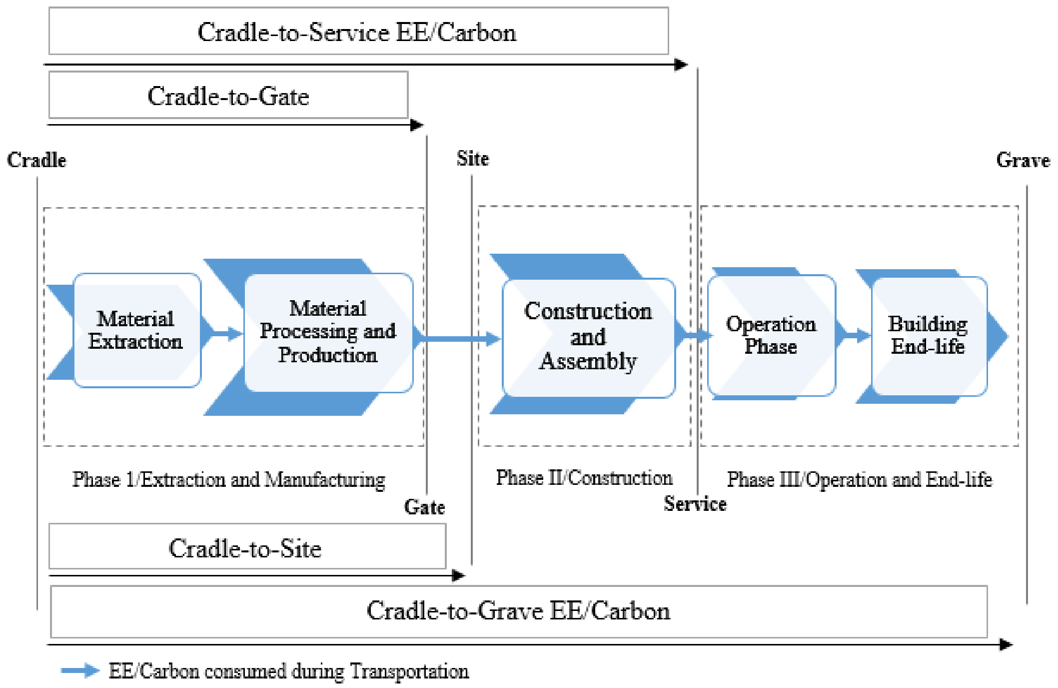


Figure 2-11: Embodied Energy/Carbon during Building's Lifespan

Adapted from (Ali Akbarnezhad & Xiao, 2017)

On the other hand, Greenhouse gas emissions (GHG) from buildings mainly occur from the utilization of fossil-fuel-based energy, via the direct use of fossil fuels and due to the use of other energies which has been generated from fossil fuels. Construction Materials are also generated Considerable GHG emissions. The greenhouse gas emissions is a composition of 76% carbon dioxide[3], 13% Methane, 6% Nitrogen oxides and 5% Fluorocarbons (Ottmar et al., 2014). In much literature, the word "Carbon" is used often to cover either carbon dioxide (CO_2) or carbon dioxide equivalents (CO_2-e) that counts CO_2 and additional gases with significant global warming potential.

According to the United Nation's Intergovernmental Panel on climate change, IPCC (2001): GHG emissions are the primary contributors to global warming and the temperature of the earth is raised from 0.3°C and 0.6°C during the last 150 years. The figure is expected to rise to a global average of about 4.5°C by the year 2100 if no environmental measures are pioneered[4] (Ritchie & Roser, 2020). **Figure 2-12** shows the global greenhouse gas emissions and the expected global temperature rise by 2100.

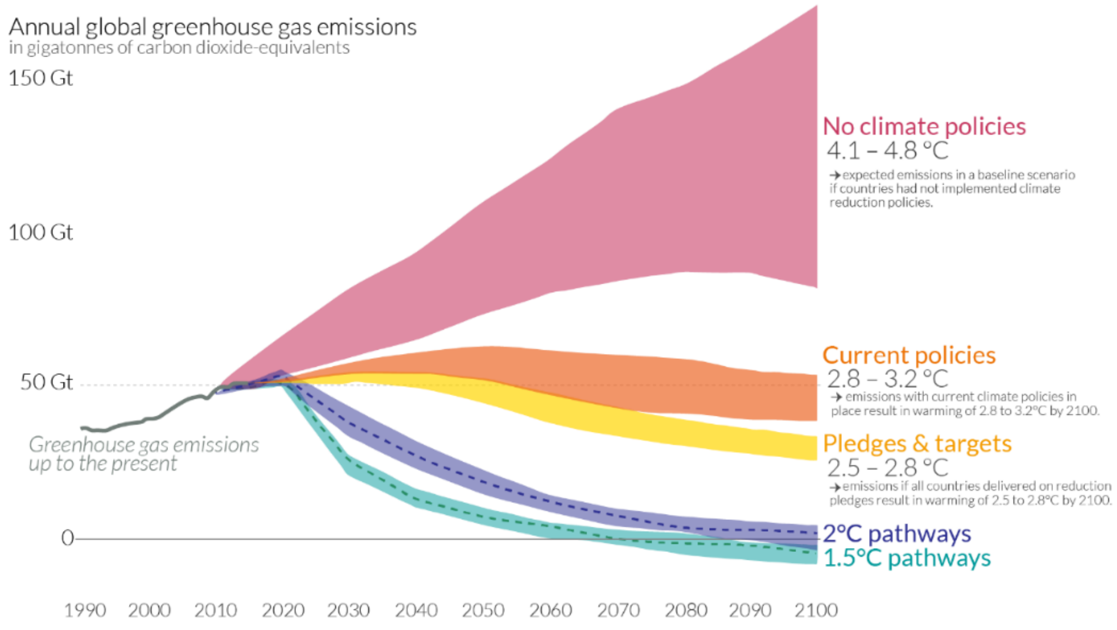


Figure 2-12: Future global greenhouse gas emissions and global warming scenarios

Source: (Ritchie & Roser, 2020)

[3] As stated by the Global Alliance for buildings and construction in the 2018 global status report: The CO_2 emissions resulting from material use in buildings account for 28% of the annual buildings related to CO_2 emissions. Most of these emissions are a result of cement and steel manufacturing, which have high process emissions and are used in large quantities. Aluminium, glass and insulation materials are secondary contributors.

[4] **Improving energy efficiency** to produce a given building product, and **transitioning to low-carbon alternatives** by substituting carbon-intensive products with a lower carbon footprint.

Moreover, Sagheb, Vafaeihosseini, and Kumar (2011) stated that industrial processing shares about 16.8% of the annual GHG emissions in which Carbon Dioxide (CO_2) is sharing around 80% of these emissions, thus, the CO_2 is a significant contributor to increasing the global temperature affecting in climate change. Besides, the GHG emissions are considered to be more harmful because they are initiated within a very short time at the beginning of a building life cycle, bearing in mind the short and the mid-term climate change mitigation targets in comparison to the use phase emissions, which occur in a long time during the operation phase of the building (Säynäjoki, Heinonen, & Junnila, 2012). However, the term embodied carbon has been defined by Sturgis and Robert (2010) as the generated carbon dioxide emissions from the construction of buildings, their renovated and consequent maintenance.

Another explanation that can be added to this part is that: there are many uncertainties regarding the expected amount of GHG emissions during the building use phase, as many factors related to the future of energy generation technology, building energy efficiency renovations and actual emissions might completely differ from the recent values (Amalia, Antti, Jukka, Juha-Matti, & Seppo, 2015). This further emphasizes the significance of the GHG emissions at the construction stage, as they inhibit less vagueness compared to the operation phase emissions. For example, Hong et.al (2015) estimated the GHG emissions during the construction phase of a case building in the context of China. The results showed that 97% of all GHG emissions were indirect emissions (emissions from materials production and construction-related offsite human activities). The on-site electricity used and the production of building materials were the main two significant contributors to the direct and indirect emissions.

Also, as stated by Ízzet Yüksek (2015), the proportion of the consumed energy during the production of the building materials, to the total energy consumption during the building lifetime is considered to be approximately 50 years and it is possible to change between 6% and 20% depending on many factors such as climate and construction systems.

Different types of building materials have a wide dissimilarity of EE and they release CO_2 at different scales during their lifetime. However, the selection of appropriate building materials can significantly reduce CO_2 emissions and open opportunities to construct more energy-efficient buildings. Energy and harmful emissions may be considered as being embodied with building materials. However, EE can be regarded as the amount of energy needed to process, assemble, demolish building materials in any construction project, and to calculate this EE, an accounting methodology is needed to sum up all the input energy over the material's Lifespan (Sabnis, Mysore, & Anant, 2015). See **Table 2-5**

BUILDING MATERIALS	EMBODIED ENERGY[5] AND CARBON DATA	
	EE-MJ/Kg	EC-kgCO_2/kg
Aluminum (General)	155	8.24
Aggregate (General)	0.1	0.005
Common Bricks	3	0.22
Cement (Portland)	4.6	0.73
Cement with 25% flyash	3.52	0.62
Cement with 50% flyash	2.43	0.42
Cement Mortar (1:4)	1.21	0.177
Concrete (Plain)	0.95	0.13
Concrete (Reinforced)	1.21	0.148
Concrete Blocks (8mpa)	0.6	0.061
Concrete Precast	2	0.215
Glass (General)	15	0.85
Steel (General)	24.4	1.77
Stone	1	0.056
Timber	8.5	0.46
Plywood	15	0.81
Marble Tiles	3.3	0.187
Ceramics	5	0.349
Plastics	61	2.2

Table 2-5: EE and Carbon Coefficient for Common Building Materials Adapted from (Sabnis et al., 2015)

There are big differences in the embodied energy (EE) content of each building material, for example, concrete and steel have a huge environmental impact regarding their EE if compared with other materials like wood. Founded in most previous studies, the production and the use of wood and wood-based materials in the construction industry guides to much lower EE, reduction in CO_2 emissions and life-cycle energy compared to inorganic materials such as concrete and steel (Bejo, 2017).

Most of the previous studies have been focused on optimizing operating energy (OE) of the building by using new advanced materials for building envelope and equipment, however, more research is needed to fill the gap regarding the selection of energy-efficient building materials to achieve the overall sustainable target of the building.

[5] Currently, embodied energy is estimated by calculating the non-renewable primary energy consumption as the main indicator. Nevertheless, in some assessment methods and standards, renewable energy is added to the total primary embodied energy either independently or as an indicator.

2.2.2 The Evaluation Methods for the Embodied Energy (EE)

The estimation of EE is a challenging and more complex task than the calculating of OE due to the unavailability of quality data and a standard evaluation method. Most of the estimation methods are different in their energy attention and they use different sets of energy inputs, thence their results are not comparable (Dixit, 2017a). In general, three methods are used to estimate the embodied energy, including the process-based life cycle assessment, input-output-based IO-LCA and hybrid LCA (Azari & Abbasabadi, 2018a). Nevertheless, the above-mentioned estimation methods have been used also to evaluate wider life-cycle environmental impacts in many previous studies.

The process-based LCA is a leading methodology for the evaluation of EE, the quantity and the type of the energy is calculated and recorded in every step throughout the building life cycle, from material extraction and manufacturing, through transportation and construction, to maintenance and demolition phases. However, the operation energy OE is excluded from this method, in which it can be separated evaluated for the entire life cycle of the building. As stated by International Standard Organization, ISO 14040 and ISO 14044[6] respectively, the process-based LCA can be conducted in four stages, goal and scope definition, inventory modelling, impact assessment, and an interpretation of results (ISO 14040, 2006; ISO 14044, 2006). The limitation of this method is the level of complexity and time-intensive needed to define the system boundaries which in the long term leads to an underestimation of the final EE results.

The second method is the input-output (IO)-based life cycle assessment (LCA). This method is created to solve the limitation of the process-based LCA. The system utilizes economic data problems for the entire construction sector. Furthermore, the method assumes a consistent and homogeneous proportion of energy flow and consumption and product quality, for the whole sector which may not be applicable and accurate as the values and prices are varied across industries (Dixit, 2017b).

The third technique is the Hybrid LCA, which is a combination of process-based LCA and IO-based LCA. The method takes advantage of both previous LCA methods. However, the Life cycle assessment methodology can be used to evaluate construction and materials processes (Bilec, Ries, Matthews, & Sharrard, 2006).

[6] The International Organization for Standardization ISO is worldwide federation of national standard bodies. It is role of preparing International Standards is normally handled though it is technical committees. This second edition of ISO 14040, together with ISO 14044:2006, cancels and replaces ISO 14040:1997, ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000, which have been technically revised.

On the other hand, the calculations of EE is rather complex since many technical and physical issues are presented regarding the combination of various materials in buildings. However, as stated by Maassarani, Mohareb, and R. (2017), it is better to calculate the EE from the conceptual design stage of the building as it will help the project stakeholders to make informed design decisions to achieve a more green building.

2.2.3 Life Cycle Energy Analysis-EE Case Studies

Previously, embodied energy has been conventionally overlooked on building energy assessment, as they are only represented a small proportion when compared with the operational used over the lifespan of the buildings. Recently Many Studies have been investigated the life cycle energy and the significant share of the material's embodied energy in the total consumed energy. However, the application of energy-efficient materials has been considered as an effective way of minimizing the energy requirements and increasing the lifetime performance of the building.

A study by Thormark (2001) showed that embodied energy can make a remarkable share in the total energy use in a low energy building and it can account for as much as 40% of total energy use. However, Another Study by Feist (1996) showed that the total energy needed in a low-energy building can be higher than in a building with higher amounts of operational energy, and this because a large quantity of energy is required for the production and maintenance of the technical equipment. For that reason, it is more essential to pay attention to the energy use for producing materials as it plays an essential role in total energy consumption.

Manish Dixit (2017b) reviewed numerous literature studies (from 1975 until 2016) to show the parameters causing variations in the results of EE in residential buildings (single and multi-family types) and how much these parameters differ across the examined studies. The case studies cover the regions of Oceania, Europe, North America, and Asia and a 50 years' service life is assumed for all cases. The research findings suggested that EE can account for 0.9-16.3, 0.9-23.1, 0.9-19.2, and 0.9-6.6 GJ/m^2 in brick, concrete, steel and wood-built residential buildings, respectively. The author noted that the variation of these parameters is due to the lack of complete, precise and directive EE data.

Aktas and Bilec (2012) studied the impact of a lifetime on U.S. residential buildings LCA. The research found that the average building lifetime is 61 years and has a linear growing trend. The research investigated the energy used during the pre-use phase, which includes initial materials use, construction and energy used for transportation. The initial

EE in the examined buildings ranges from 1.7-7.3 GJ/m^2 in regular residential buildings (with a mean of 4.0 GJ/m^2), while it ranged from 4.3-7.7 GJ/m^2 in low energy residential buildings (with a mean of 6.2 GJ/m^2). However, the last higher average in the low energy residential buildings appeared due to the use of thicker building envelopes and Insulation.

Furthermore, Grace Ding (2004) investigated previous studies on EE content of buildings and observed that, the initial EE in residential buildings varied in a range of 3.6-8.76 GJ/m^2 of gross floor area with a mean of 5.506 GJ/m^2, and from 3.4-19 GJ/m^2 in commercial buildings with a mean of 9.19 GJ/m^2. The research also suggested that demolition energy (DE) creates a share ranged between 1-3% of the overall initial EE.

On the other hand, several well-established studies have been done regarding the impact of OE on total energy consumption and many codes and guidelines have been launched to make low energy building or net-zero energy building. In Contrast, more research is needed to evaluate the impact of EE on energy consumption and fossil fuels emissions in buildings. However, regarding the previously mentioned parameters affecting the evaluation of the EE in buildings, the geographical location considers as a major parameter influencing the estimation of EE. For example, EE represents a smaller percentage in the life cycle assessment in the heating-dominated regions (Buildings use high OE) compared with cooling-dominated or moderate regions (Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013). In recent research Koezjakov, Urge-Vorsatz, Crijns-Graus, and van den Broek (2018) examined the relationship between heat demand and the EE using Dutch residential buildings as a case study. The findings concluded that EE use in a standard house is about 10-12% of the total energy use and 36–46% in energy-efficient dwellings due to the use of large insulation size in the second type. Additionally, Some researchers demonstrated that embodied emissions for a building in heating-dominated regions account for 10% of it is life cycle emissions (Azari & Abbasabadi, 2018a).

Moreover, some studies investigated the impact of EE and OE in the life cycle energy use of buildings. For example, Sartori and Hestnes (2007) examined the contribution of EE and OE in the life cycle energy of 60 conventional and low energy buildings from nine countries, the case studies included residential and non-residential buildings types. The results indicated that EE is responsible for 2–38% of total energy use in conventional buildings, and between 9–46% of the total energy use in low-energy buildings. Another study conducted by Chastas, Theodosiou, and Bikas (2016) examined 90 residential buildings from literature in terms of life-cycle energy analysis, the researchers concluded that the share of EE is 6-20%, 11-33%, 26-57%, 74-100% in conventional buildings, passive buildings, low-energy buildings, and net-zero-energy buildings, respectively.

T. Ramesh et al., (2010) conducted a review on a life cycle energy analysis of 73 cases of residential and office buildings among 13 countries and concluded that 10-20% is the share of EE in the total energy used in the examined buildings, while the rest (80-90%) is the OE contribution. T. Hong, Ji, Jang, and Park (2014) analysed the EE and the GHG emissions of an apartment building project using Hybrid LCA approach by defining the construction process into three phases; materials manufacturing, transportation and on-site construction stage. The results showed that the manufacturing stage of the building materials has the largest amount of energy consumption and GHG emissions. The amount of energy consumed is 94.89%, 1.08%, and 1.03% of the total energy for manufacturing, transportation and construction, respectively. In the same order, the results of the global warming potential values were 95.16%, 1.76% and 3.08%.

Also, Xiaocun Zhang and Wang (2016) examined the carbon emission on three different buildings in the context of China by using the hybrid LCA method. Their results showed that material manufacturing is the major contributor to GHG emissions accounting for 80-90% of the total emissions, and the foundation and the main structure were the sub-projects that contributed to more than 60% of the building embodied emissions.

Furthermore, Bansal, Singh, and Sawhney (2014) analyzed the effect of construction materials on EE and the cost of buildings based on a case study covering 122 residential buildings in India and concluded that the used EE amount fluctuated between 2092-4257 MJ/m^2 with various building materials. The research revealed that the EE and construction cost got fewer rates of 40% and 20%, respectively, in the houses by involving energy-efficiency measures and alternative building materials.

Moreover, from the previous literature reviews, wide EE variations have been noticed and many parameters have represented their effect on the total EE of the building and it is difficult to predict the exact value of the EE rather than it is suggested to present it as a range of values. Debnath, Singh, and Singh (1995) calculated the total energy consumption of major building materials during the construction phase for three building typologies; single, double and multistoried buildings in India. The findings of their research concluded that steel, concrete and bricks are the materials that contributed to high energy consumption in all three examined case studies. Another notice observed from the research results that the energy consumption decreases as the floor area increases, for example, in a single-story unit, if the floor area increases from 50 to 200 sqm, the energy consumption decreases from 5 to 4.1 GJ.

Dimoudi and Tompa (2008) carried out a study on two office buildings in Athens, Greece in terms of the EE and the equivalent emissions of carbon dioxide (CO_2) and sulfur dioxide (SO_2). The EE of concrete and reinforcement steel shows the largest component in the total EE of the assessed buildings in a range of 66.73% to 59.57%, whereas the building envelope's materials represent a lower but significant percentage in the total EE. One of the most important notices is that the EE of the paints is less than 1% and hence paints have a low impact on the overall EE compared with other examined building materials in this study.

Moreover, Heravi, Nafisi, and Mousavi (2016) carried out studies on 14 residential buildings to evaluate the energy consumption during production and construction phases based on the LCA approach in Tehran, Iran. They proved that the production of steel is a more energy-consuming process than the production of concrete (27% less than steel). These results are consistent with the studies made by Xing, Xu, and Jun (2008) and Foraboschi, Mercanzin, and Trabucco (2014).

In addition to that, some studies investigated Comparative life cycle assessment of flooring materials, for example, Nicoletti, Notarnicola, and Tassielli (2002) studied a comparative Life Cycle Assessment between ceramic and marble tiles in the context of Italy. The research revealed that the energy consumption of ceramic tiles is of a high amount compared to marble tiles, due to the high temperatures and energy used to fire the ceramic during the production stage. Also, Bovea, Díaz-Albo, Gallardo, Colomer, and Serrano (2010) in previous research concluded that ceramic tiles have high levels of energy consumption and atmospheric pollution exceeded the limits required by environmental regulations.

Yohanis and Norton (2002) studied the operational and embodied energy for a generic single-storey office building in the UK to show the relationship between the building's envelope and the life cycle energy. The research showed that glazing has a huge impact on both embodied and operational energy when the glazing area exceeded more than 55% of the total façade area, the EE is found to be low but the OE is higher.

Treloar, Fay, Ilozor, and Love (2001) investigated the relationship between the EE and the height of the building. However, five tall buildings (Office Buildings) ranging in a height from a few stories up to 52 stories have been evaluated. The findings of the research revealed that tall buildings are consuming more energy than low-rise buildings, and it can reach 60% higher energy in tall buildings.

Shukla, Tiwari, and Sodha (2009) studied the EE of the adobe house and its effect on the environment located in Solar Energy Park, Indian Institute of Technology Delhi, New Delhi. The house has been constructed by using low-energy building materials. The Walls constructed with stabilised soil cement blocks, mud plaster, white-wash for interior walls, the vaulted roof made of adobe with mud mortar, and the house foundation made with plain cement concrete applying brickbats as coarse aggregate. The results showed that a reduction in energy consumption has been noticed compared to the regular reinforcement concrete building (370 GJ can be saved every year), and the EE used for the maintenance of adobe house equal to 12% of the overall embodied energy. Also, the EE of the adobe house was discovered to be 4750 MJ/sqm of the total built-up area.

2.2.4 Embodied Energy and Embodied Carbon Reduction Strategies

The reduction of EE in buildings is often connected to the use of local and renewable materials as well as lightweight construction systems (fewer construction materials can be used in the structure and building envelopes). As mentioned previously, the use of local materials have the advantages of reducing transportation cost and energy consumption (Fuel), thus decreasing the EE of the selected building materials. However, the selection of appropriate building materials can play a major role in reducing the intensive EE in the buildings and the criteria for the selection should include but not limited to the use of materials with renewability potential, produce locally, have recycled content and recyclability perspective and the possibility to reduce waste.

Furthermore, several studies tried to reduce the EE of the building, for example in research done by Foraboschi et al. (2014), the floors are the most important part of the structure to lower the EE of the entire building. In the research, several tall buildings have been investigated to assess the embodied energy. The findings of the research revealed that by increasing the number of columns, reducing the span of beams and floors, minimizing the floor thickness, and selecting lower EE for lightweight materials, the EE of the whole building will be decreased sharply.

In another study, Buchanan and Honey (1994) investigated the impact of EE and GHG emissions from the construction of the building with reference to buildings in New Zealand, the research suggested that the use of renewable energy resources, minimizing fossil fuels burning and the implementation of effective construction techniques can improve the energy performance of the building. Besides that, a shift from concrete and steel to alternative materials can make a significant decrease in CO_2 emissions.

Moreover, Pere Fuertes (2017) in recent research considered architecture as a resource to study the impact of the embodied energy in the existing structure and how the EE could be a major factor in developing more sustainable strategies. The research highlighted five approaches to be considered in the renovation of existing buildings in order to improve the EE and the programmatic performances of the building, through compatibility (between existing construction and the new programs) and adaptability (capacity to reuse) as re-programming strategies and Complementarity (capacity to be approved for more efficient performance), durability and reversibility (a rearranged method that effects in the increasing of building's lifespan) as design strategies.

Kumanayake, Luo, and Paulusz (2018) proposed several strategies for the reduction of building's carbon emissions in Sri Lanka including; build up designs that save quantities of materials, modifying the existing concrete properties, using low carbon alternative materials, integrating carbon emissions as evaluation criteria for energy-efficient buildings, encouraging the use of recycled building materials and promoting the use of eco-labelling for building materials. Further research by Wan Omar (2018) revealed that by implementing low embodied energy and low embodied carbon building materials and components, a total energy reduction in the EE and embodied carbon was achieved in the Malaysian's case studies with a value of 43% and 41%, respectively.

In a recent study, Shadram and Mukkavaara (2019) applied a multi-objective optimization approach to show the effect of several energy efficiency measures (EEMs) on the embodied and operational energy in a case study of Swedish residential buildings. However, two sets of EEMs have been investigated, the first set dealt with the building's shape, orientation, window to wall ratio (WWR), and basic building materials and this set can be applied and modified during the early design stage. The second set included EEMs which can be integrated later in the design phase. The findings of the results proved that a higher reduction on the overall life cycle energy (Almost 5 times greater) has been achieved by applying optimal solutions of the first EEMs set (ranged from 2175.2 to 3803.8 GJ) more than in the second EEMs set (with a value ranged from 418.6 to 625.6 GJ).

2.2.5 Alternative Building Materials

Dominant materials which prevailed in the ages of mankind such as stone, timber and mud are extracted from natural resources and play a significant role in each era, for example, the stone age, the age of steel, the bronze age, the iron age (Ashby, 2009) as shown in **Figure 2-13**.

Building materials drew from natural resources are less harmful to the environment and consume less energy during their manufacturing process. In some parts of the world, the use of earth, grass, animal dung and plant residues as main building materials is a very common construction practice up to date (Mpakati-Gama, Sloan, & Wamuziri, 2012). However, the use of natural materials has been associated with problems related to durability and stability which lead to the exploration of more durable building materials.

The development of the construction industry and urbanization leads to the use of modern building materials which exploiting nature and natural resources. Materials like steel, aluminium, cement and ceramic are consuming high energy throughout their lifespan, from the materials extraction and manufacturing through the construction and operation stages till the end of the building life. Therefore, the necessity of finding alternative materials is very urgent to reduce the building environmental impact and to achieve sustainable development goals in the coming future, the literature in this part is very rich.

Even though there is no common definition of the ABMs in literature, but they can be defined as material or combination of materials that use available natural resources instead of conventional non-green resources to enhance the inefficient consumption of energy and supplies and to achieve sustainability in buildings.

Reddy and Jagadish (2003) observed that 50% EE reduction can be achieved by using alternative building materials. In their research, a comparison study between the alternative and conventional building materials in terms of EE consumption has been completed. Results showed that Soil-cement block masonry (for walling), lime-pozzolana mortar and the stabilised mud block filler slab roof are the most energy-efficient materials compared with the traditional systems used in India. The research concluded that load-bearing soil-cement block masonry with a stabilized mud-brick roof as a complete system lead to a 62% and 45% reduction in the overall EE when compared to RC framed structure and burnt clay brick masonry and RC solid Slab systems, respectively.

Another study by Venkatarama Reddy (2009) proved that the use of alternative materials and technologies results in a reduction of 50% in the total EE of the building. In the same study, a list of low-carbon alternative building materials such as blended cement, compacted fly ash blocks, rammed earth walls have been presented (See**Table 2-6**).

Type of Building Materials	**Energy per Unit (GJ)**
Burnt clay brick masonry (m^3)	2.00–3.40
SMB masonry (m^3)	0.50–0.60
Fly ash block masonry (m^3)	1.00–1.35
Stabilized rammed earth wall (m^3)	0.45–0.60
Non-stabilized rammed earth wall (m^3)	0.00–0.18
Reinforced concrete slab (m^2)	0.80–0.85
Composite SMB masonry jack-arch (m^2)	0.45–0.55
SMB filler slab (m^2)	0.60–0.70
Non-reinforced masonry vault roof (m^2)	0.45–0.60

Table 2-6: Low-carbon embodied materials and assemblies
Adapted from (Venkatarama Reddy, 2009)

Shams, Mahmud, and Amin (2012) demonstrated that the use of alternative building materials can lead to approximately a 52% reduction of the total EE and 45% of total embodied carbons. The research also showed that aluminium, steel and ceramics should be used less due to their higher Co_2 emissions compared to glass, timber and brick. The use of alternative materials such as cement concrete with 50% fly ash, marble tiles instead of ceramic tiles and cement mortar with 50% fly ash, can significantly decrease the Co_2 emissions and lead to better energy-efficient buildings.

Furthermore, Asif et.al (2007) examined a life cycle assessment of a three-bedrooms semi-detached dwelling home in Scotland. Five different construction materials have been examined in a life cycle assessment approach. The findings of the study noted that concrete, timber and ceramics are the three major energy-intensive materials which accounted for 65%, 13% and 14%, of the total EE of the examined home, respectively. Moreover, the research approved that concrete and mortar are responsible for 99% of the total building CO_2 emissions.

Additionally, concrete is a construction material widely used in building and other infrastructure applications. It is second only to water as the most-consumed resource on the earth. However, the impact of cement and concrete on the environment is huge due to the use of clinker to produce the cement. For example, the specific energy consumption of clinker varies from around 3.40 Giga Joule per ton for the dry process to about 5.29

Giga Joule per ton for the wet process (Madlool, Saidur, Mohammed, Solangi, & Rahim, 2012). Recently, many studies have been established to minimize the amount of clinker and replace it by using complementary cementing materials (CCM) as an alternative material such as fly ash, limestone, recycled aggregate and slag blast furnaces. For example, Habert and Roussel (2009) evaluated two systems for sustainable concrete mix-design, the first one is the replacement of clinker in cement by mineral additives to reduce the material's environmental cost. The second system is reducing the volume of the concrete by enhancing its performance. The results showed that, in France, a 15% reduction in the CO_2 emissions achieved by using the first method, while the second option can lead to a 30% reduction in the total CO_2 emissions.

Furthermore, numerous waste materials are generated from the manufacturing processes and the construction of the buildings, and the impact of these wastes become one of the major environmental concerns all over the world. The use of consumer wastes such as plastic, glass and ceramics as a secondary aggregate will help in reducing the embodied carbon emissions in the building.

As stated by Siddique, Khatib, and Kaur (2008) the use of these wastes can make the concrete more economical and they can help in solving the problem of materials disposal. Another product produced from the agricultural industry wastes is the straw bales which has been used as wall fillers in low energy buildings. However, the straw bales can be an effective alternative material (can be used as Thermal and wall material) if good moisture protection and good construction techniques applied to the building during the construction phase (Goodhew, Carfrae, & De Wilde, 2010).

Briga-Sa et al. (2013) studied the applicability of woven fabric waste (WFW) and woven fabric sub-waste (WFS) as alternative thermal insulation building materials, the study revealed that the integration of these materials to the external wall of the building enhances the thermal behaviour of the wall in a range of 56% for the WFW and 30% in the case of WFS. The research concluded that the results of the thermal results obtained by using these new insulation materials are similar to the values obtained from the application of conventional insulation materials like extruded polystyrene (XPS), mineral wool (MW) and expanded polystyrene (EPS). In the same direction, Binici, Eken, Dolaz, Aksogan, and Kara (2014) investigated the use of sunflower production waste and cotton textile waste as environmentally friendly insulation material and results showed satisfactory insulation materials met the Turkish standard.

A star (*) shows the date at which an element was first specified

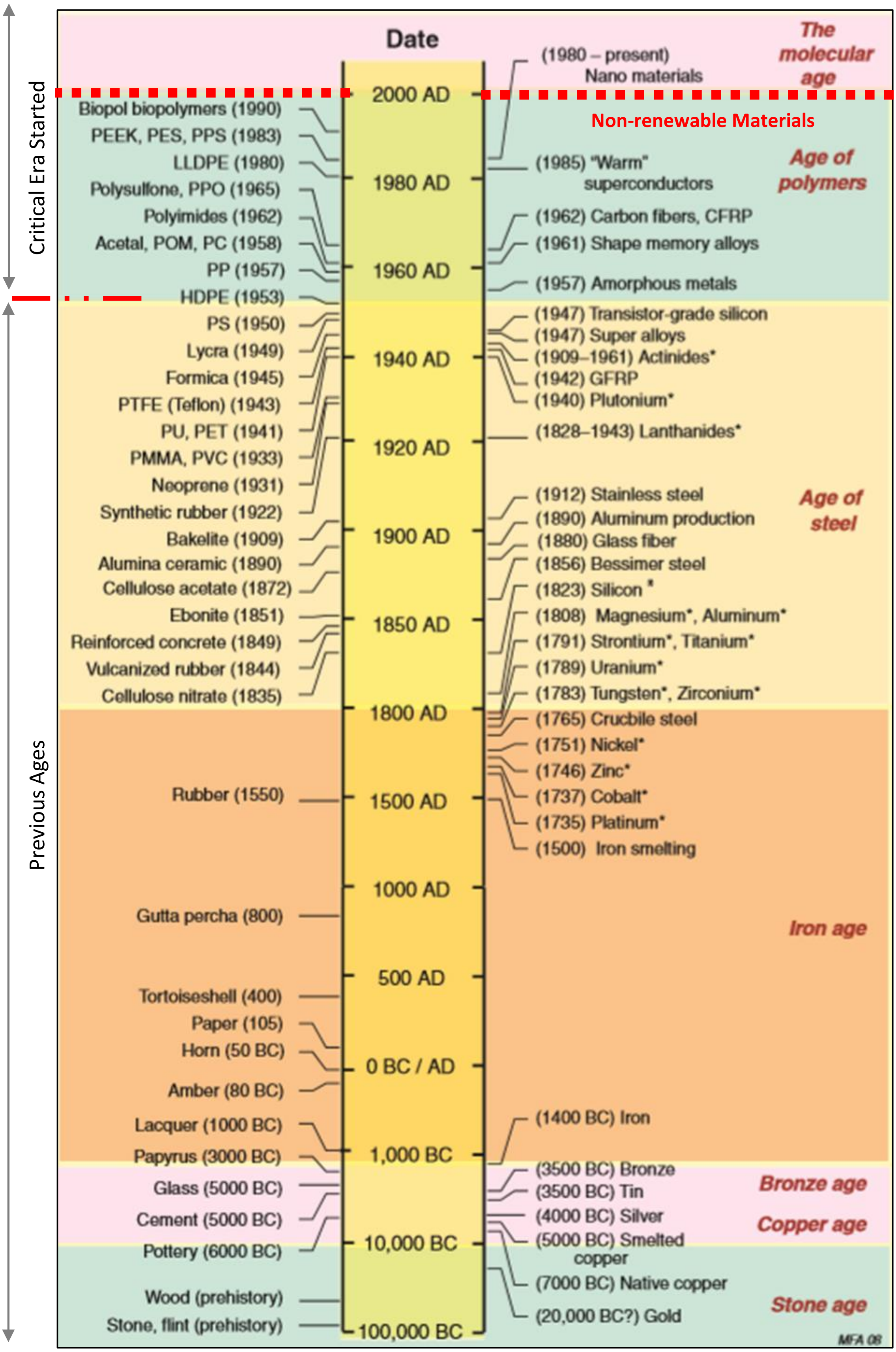


Figure 2-13: The materials timeline (Nonlinear Scale)

Adapted from (Ashby, 2009)

Additionally, Srikonda Ramesh (2011) investigated the EE of various Vernacular Building Materials for Roofing and Terracing Options in India, the researchers concluded that channel units roofing[7], filler slab roofing[8] and mud phuska terracing[9] can cut down the EE of the building significantly so as to sustain the energy in the building industry.

Moreover, Mansour and Ali (2015) investigated the usability of waste plastic bottles as an alternative sustainable building material to replace the traditional concrete block. A masonry wall has been constructed after filling the plastic bottles with either dry sand, saturated sand, or air, and cement mortar as a binder. The researchers noted that the plastic air-filled bottles can be used as a partition wall or as a loadbearing wall for one roof slab and it has good thermal properties, while the other systems showed a slight defect in the strength compared with conventional concrete block. In contrast to improving the material greenness of Concrete through combination with CCM, an entirely alternative binder to ordinary Portland cement concrete called geopolymer concrete appeared.

According to Van Deventer, Provis, and Duxson (2012), the geopolymer made from fly ash, metallurgical slags and natural pozzolans could reduce more than 80% of the associated CO_2 emissions with the manufacturing of cement which can reduce the construction environmental impact. However, various geopolymeric products have been introduced as alternative materials such as In-situ geopolymer foam, Lightweight fly ash-based geopolymer concrete sheets using EPS beads, Fly ash-based geopolymer bricks and Fly ash-based geopolymer solid and hollow blocks (Singh, Ishwarya, Gupta, & Bhattacharyya, 2015). More information about the available sustainable alternative materials is presented in chapter three.

2.2.6 The effect of Material Selection on the Building's energy performance

Building materials are used in many application within the construction industry and each discipline focus on how to identify the best selection method to achieve their needs (Maskell et al., 2018). Different types of building materials have a wide variation of embodied energy and emit CO_2 at different levels during their lifetime. However, the selection of appropriate construction materials is recognized to be the very basic way to apply sustainable design ideas in buildings which can considerably reduce CO_2 emissions

[7] These units are reinforced cement concrete elements channel shaped in section and 2.5 to 4.2m long.

[8] An effective roofing system which is based on the concrete portions replaced by the filler materials such as bricks, terracotta tiles, cellular concrete blocks and packed mud blocks.

[9] One of the conventional ways of waterproofing commonly used over reinforced concrete roofing.

and open the opportunity to create a more sustainable and energy-efficient building (Joanne Mary, 1997).

The selection of suitable construction materials for any project starts by making evaluation criteria and rating systems to compare different products by using the concepts of higher and lower points, excellent and poor and even A, B, C, D letters system. After that, a score can be obtained for each material by totalling the points given by the rating systems and the selected materials will be integrated into the project specifications. However, this concept is very complex as there are many interrelationships in terms of what are the most important criteria for a given product. Therefore, the need for a multi-criteria selection tool to evaluate building materials is highly required to solve this problem and to mitigate past experience selection methods (Keysar & Pearce, 2007).

According to Takano et al. (2015), there is no perfect material that can be fit in all cases, thus it is very important to select the construction material according to the requirements of each case in the project individually. Furthermore, the link between material selection and energy optimization in the building has been shown in many recent studies as an effective solution to reduce the negative impact of the buildings on the environment. For instance, Thormark (2006) examined the effect of material selection on the EE and recycling potential in a low energy building in Sweden and found that approximately 17% of energy reduction can be decreased or 6% increased through material substitution.

Moreover, Basbagill, Flager, Lepech, and Fischer (2013) studied the effect of material choice and thickness on the total EE of the building during the early design stages. The case study investigated four elements including substructure, shell, interiors and services. The findings of the research showed that a significant reduction in the EE can be achieved by changing the thickness and specifications of the cladding and glazing materials regardless of building design configuration.

Additionally, many studies have been established to show the effect of materials selection on the OE of the building. For example, Dodoo, Gustavsson, and Sathre (2012) analyzed the effect of material thermal mass on the amount of heating energy in a building located in Vaxjo-Sweden by comparing concrete and wood frames. They noted that concrete frame building has a slightly lower space heating (0.5-2.4%) compared to wood-frame due to the high thermal mass effect of the concrete.

Additionally, Zhu, Hurt, Correia, and Boehm (2009) compared the energy performance of insulated concrete wall system (mass wall) and a conventional wood frame construction of exterior walls of a zero-energy house in las vegas-Nevada and concluded that wood construction requires higher space heating but lower space cooling compared to concrete construction.

Furthermore, Zabalza Bribián et al. (2011) studied the energy and the environmental specifications of building materials to provide guidelines regarding the material selection in the design of new and existing buildings. The study concluded that choosing building materials with high EE causes a high level of energy consumption during the building production stage and even affects the energy of the building through its operational stage by increasing the demand of energy consumption to meet heating, air conditioning and cooling loads of the indoor spaces.

The literature is numerous in this regard, however, it can be concluded that the selection of building materials requires the use of natural and renewable materials which has less energy-intensive and pollution on the environment, local materials that can reduce the energy consumption and the construction cost, recyclable materials that provide considerable resources and energy saving, and durable materials which can save the energy and maintenance cost throughout the building's lifespan.

2.3 Sustainable Development Goals (SDGs)

2.3.1 General Overview

In September 2015, The united nations general assembly (Leaders from 193 countries of the world) adopted the seventeenth sustainable development goals as an action plan to transform the world (people, planet and prosperity) by the year 2030[10]. However, several environmental, economic and social development concerns, such as health and well-being, poverty, hunger, quality education, gender equality, climate action, water, sanitation, energy and environment and peace and social justice have been covered by the UN 2030 Agenda (United Nation-UN, 2015). See **Table 2-7**

The new 17 SDGs and the 169 associated targets are linked to the previous three pillars of sustainable development: the economic, social and the environment in an attempt to encourage action over the next years to transform our world for a sustainable planet. The 2030 Agenda has been motivated by the following reports: Brundtland report (1987), the UN conference on environment and development (Rio Earth Summit) (1992), the

[10] The United Nations Development Programme (UNDP) is one of the leading organizations working to fulfil the SDGs by the year 2030. Present in nearly 170 countries and territories, they help nations make the Goals a reality. They also champion the Goals so that people everywhere know how to do their part.

Millennium Declaration (2000), and the UN Conference on Sustainable Development (Rio+20) (2012). See **Figure 2-14**

Figure 2-14: The Road to the 2030 Agenda for Sustainable Developments

Adapted from (Eurostat, 2018)

The SDGs are challenging all countries to establish determined and innovative systems and strategies in order to apply these goals and targets from a global scale to a country level. However, governments and their related bodies in each country have the major responsibility to initiate roles and regulations and also to follow up and review the implementation of these goals at local, regional, national and global levels. The various goals and targets will be associated with a different degree of challenge for different countries depending on the existing development condition of each country and many other issues. However, a degree of attention and effort is needed when it comes to the implementation of these goals and targets and a critical decision is required depending on the situation of each country towards its different facilities and resources (Osborn, Cutter, & Ullah, 2015). The World Business Council for Sustainable Development (WBCSD) (2018) has conducted a global survey to investigate how companies are now working to incorporate activities with the SDGs. The survey drew responses from around 250 companies across 43 countries and four continents. The results of the survey showed that the SDG 13 (climate action) is the most ranked goal among others, with 62% of companies classifying it as an important task, while the SDG 14 (Life below Water) achieved the least rank (only 10% of companies seeing it as a major topic). The responsible consumption and production goal (SDG 12) scored the highest percentage in Europe and Asia Pacific regions whereas in north Latin America the SDG 8 (Decent Work and Economic Growth) was the highest rank.

Additionally, Eurostat (2018) established a report to show the progress towards sustainable development in the European Union context and to provide essential evidence about the current situation and what are the areas that need more focusing. The report showed that there has been moderate progress on many SDGs indicators. Furthermore, another report by Moratis (2018) in the state and face of sustainable business in Belgium confirmed that, While the overall results showed that the majority of Belgium companies consider themselves in the advance stage of implementing sustainability within their operations and strategies, the reality indicates that they are in the beginning stage. More Recently, Moratis and Melissen (2019) claimed that it has been more than three years (20% of the time passed) since the United Nations (UN) General Assembly announced the 17 indivisible SDGs, however, a lot of work is needed to realize the agenda in the rest of the coming years.

Sustainable Development Goals (SDGs)	
Goal 01	End poverty in all its forms everywhere.
Goal 02	End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
Goal 03	Ensure healthy lives and promote well-being for all at all ages.
Goal 04	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
Goal 05	Achieve gender equality and empower all women and girls.
Goal 06	Ensure availability and sustainable management of water and sanitation for all.
Goal 07	Ensure access to affordable, reliable, sustainable and modern energy for all.
Goal 08	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.
Goal 09	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.
Goal 10	Reduce inequality within and among countries.
Goal 11	Make cities and human settlements inclusive, safe, resilient and sustainable.
Goal 12	Ensure sustainable consumption and production patterns.
Goal 13	Take urgent action to combat climate change and its impacts.
Goal 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development.
Goal 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.
Goal 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels.
Goal 17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development.

Table 2-7: List of SDGs adopted by the UN General Assembly in September 2015

Adapted from (United Nation-UN, 2015)

On the other hand, by taking a closer look at the SDGs, we can say that the goals are depending on each other and they can form a negative or positive effect depends on many factors such as the level of development of each country, the governmental policies and the understanding level of the goals by the policy-makers. According to M. Nilsson, Griggs, and Visbeck (2016), the overlapping between different SDGs can make a perverse outcome if countries ignored its significance and started to implement the targets one by one. Moreover, the universal nature of the SDGs and the interactions between the goals and targets need to be considered by policymakers within different fields, thus a systematic framework has to be proposed in order to analyse the interactions between all sustainable development goals and indicators (Pradhan, Costa, Rybski, Lucht, & Kropp, 2017). The Understanding of the trade-off and the synergistic relationships between different SDGs is very essential to achieve enduring sustainable development results. Thus, a wide range of tools and analysis is needed to analyse the complexity and to achieve the goals in the rest of the years until 2030 (Måns Nilsson, Griggs, Visbeck, & Ringler, 2017).

In June 2016, Måns Nilsson, Griggs, Visbeck, and Ringler (2016) have developed a framework for understanding the interactions between SDGs. Seven points have been presented on an ordinal scale helping in classification the nature of the interactions between SDGs and targets (see **Table 2-8**). The framework provides a wide range of scales (from +3 to -3) to classify the most relationship between SDGs and their targets. Moreover, negative and positive interactions can be seen in the matrix. The positive interactions are given scores of either +3 (Invisible), +2 (reinforcing), or +1 (enabling), while the negative interactions and trade-off are scored with -3 (cancelling), -2 (counteracting), and -1 (constraining). Also, a score of 0 (consistent) is assigned if there are no negative or positive interactions between the SDGs or their targets (Måns Nilsson et al., 2016).

Furthermore, Waage et al. (2015) proposed a framework for examining the interactions between SDGs and how those interactions can be directed. The framework composed of three concentric layers in a circle to show the relationships between the 17 SDGs. However, the well-being, infrastructure and natural environment have been introduced in the inner layer, second-level, and third-level respectively. Each goal has been assigned to a specific level as a means to link health and well-being with other goals.

Until now, there is nascent literature, addressing the interactions between the SDGs and targets. For example, Coopman, Osborn, Ullah, Auckland, and Long (2016) identified a new methodology to understand the interlinkages nature of the SDGs in developed countries, focusing on the interlinkages between the targets of the SDG goal no 12 (ensuring sustainable consumption and production) and the other targets of SDGs. However, eight types of interlinkages and three categories (Supporting, Enabling and Relying) have been created for the evaluation and scoring of the interactions between SDGs and their targets.

Interaction Name	***Interaction Score***	***Explanation***
Indivisible	+3	The strongest form of positive interaction in which one objective is inextricably linked to the achievement of another. For example, ending all forms of discrimination against women and girls is indivisible from ensuring women's full and effective participation and equal opportunities for leadership.
Reinforcing	**+2**	Aids the achievement of another goal. For example, Providing access to electricity reinforces water-pumping and irrigation systems. Strengthening the capacity to adapt to climate-related hazards reduces losses caused by disasters.
Enabling	**+1**	Creates conditions that further another goal. For example, Providing electricity access in rural homes enables education, because it makes it possible to do homework at night with electric lighting.
Consistent	**0**	No significant positive or negative interactions. For example, Ensuring education for all does not interact significantly with infrastructure development or conservation of ocean ecosystems.
Constraining	**-1**	Limits options on another goal. For example, Improved water efficiency can constrain agricultural irrigation. Reducing climate change can constrain the options for energy access.
Counteracting	**-2**	Clashes with another goal. For example, Boosting consumption for growth can counteract waste reduction and climate mitigation.
Cancelling	**-3**	Makes it impossible to reach another goal. For example, Fully ensuring public transparency and democratic accountability cannot be combined with national-security goals. Full protection of natural reserves excludes public access for recreation.

Table 2-8: A draft framework for understanding SDGs interactions

Adapted from (M. Nilsson et al., 2016)

2.3.2 The link between Buildings, Construction Industry and Sustainable Development Goals (SDGs)

The 17 SDGs are wide-ranging, from zero poverty and hunger to peace justice and strong institutions, however, there are other several goals in which building can have a significant contribution to achieve them. The construction industry can contribute widely to achieving the UN sustainable development goals (SDGs); the industry utilizes a considerable amount of materials, energy and natural resources. Hence, many local and global challenges such as climate change, energy, water, health and well-being are significantly affected by the built environment (Alawneh, Mohamed Ghazali, Ali, & Asif, 2018). Also, the construction industry plays a vital role in economic growth, social progress and in offering effective environmental protection which are the three elements of sustainable development (Aysin Sev, 2009).

Over the past years, the concepts of "sustainable building" or "green building" have been introduced globally to meet the global contemporary challenges of achieving continuing sustained development (B. Wen et al., 2020). In this regard, the world green building Council -WGBC (2019) identified that green buildings can participate positively to meet sustainable development goals. The WGBC proposed detail of three infographics on their website to show how a green building can contribute to achieving nine SDGs. See **Figure 2-15**

Up to date, there is a growing body of literature studying the connection and interaction between building and SDGs. For example, Giacomo Di Foggia (2018) studied the link between energy-efficient measures in buildings (EEMs) and sustainable development goals (SDGs). The study linked the energy-efficient buildings to SDG11 (Make cities and human settlements inclusive, safe, resilient and sustainable) and SDG13 (Take urgent action to combat climate change and its impacts) aiming to enhance the EE of the building, reduce the energy consumption and improve the indoor comfort levels. The finding of his research indicated that the implementation of effective energy-efficient measures and strategies can lower the cost of the building, contribute to sustaining the principal objectives of the current climate and energy policies, and promote global environmental well-being.

In recent research, Alwaneh et. al (2018) proposed an index to evaluate the contribution of water and energy efficiency measures in green building to achieve the UN SDGs. The finding of the research stated that the implementation of LEED v2.2 water efficiency credits and energy and atmosphere standards participates in achieving seven SDGs in Jordan including SDG6, SDG7, SDG8, SDG9, SDG12, SDG13, and SDG15.

Moreover, Alex Opoku (2019) examined the impact and the role of the sustainable built environment concerning biodiversity conservation and the SDGs by studying the link between all SDGs in general and SDG 15 in particular. The research revealed that the efficient and responsible use of building materials has been identified as a major task where the built environment can contribute significantly to preserving biodiversity and realizing the SDGs.

Figure 2-15: Green building and Sustainable Development Goals (SDGs) Adapted from (WGBC, 2019)

2.3.3 The Contributions of Building Materials to the Achievement of SDGs

Building materials can be referred to as any material that is used for construction purposes, it can be naturally arising in nature such as clay, sand, and wood or it can be artificially made by human beings (synthetic materials) such as brick, insulation, metal and plastics (Kubba, 2017). Building Materials, belonging to over 2000 types of products and materials, commonly classified into two groups: metal materials and non-metal materials (Song et al., 2018).

Materials have been considered an essential element for building construction as far back as 400 BC (Tuflite, 2016). The first building materials were biodegradable and nondurable (for example; Leaves and animal hides). Afterwards, with the industrial revolution followed by the development of machinery and large-scale industrial production, many innovative materials have been discovered for building construction (such as Metal and Concrete). Moreover, with the continuing research; various construction materials have been available in the market to satisfy the need of creating modern architectural designs (B. N. Silva, Khan, & Han, 2018). Nevertheless, the evolution in the building materials industry has been accompanying by many environmental problems related to climate change and global warming. Building materials have been becoming part of the sustainable development concept which is becoming an important task within the construction industry aiming to reduce the negative impact of the building on the environment (Martins & Gonçalves, 2012).

The building materials generate millions of tons of waste annually resulting in large carbon dioxide emissions in the built environment. As stated by Asif, Muneer, and Kelley (2007) and Yahya and Boussabaine (2010), globally, over 40% of the application of the materials is operating in the construction of buildings, including non-renewable materials. Building materials are responsible for 10%-20% of the building's total energy consumption, from the first instance the percentages look relatively low, but by looking at the development of their production, these numbers will increase steadily in the next coming years (Talakonukula Ramesh et al., 2014; Ruuska & Häkkinen, 2014).

Building Materials dominate a great share in the total energy consumption of the building during its life-cycle and they are contributing to the total GHG emissions (J. Hong et al., 2015; Sabnis & Pranesh, 2017; Sagheb et al., 2011; Yüksek, 2015). These green gas emissions are related to the building's operational energy (OE) as well as the embodied energy (EE) of the building materials (T. Ramesh et al., 2010; Thormark, 2006).

According to the data derived from the World Health Organization-WHO (2016b), building materials (like asbestos, formaldehyde, and lead) have the potential to damage health and causes serious diseases like cancer, lung disease and reduced growth (Petrović, Vale, Zari, & Petrović, 2017b), and could create what is known as a sick building syndrome. However, if they selected well, materials can provide a better indoor environment for human beings and they can reduce the negative impacts of buildings on climate and health (Pedersen Zari, 2019).

On the other hand, since 1987, numerous building materials and products have been introduced in the construction market to show their capability to meet the international sustainable development goal. As a result, several terminologies concerning the sustainability of buildings and materials have been widely used without a clear definition (Berardi, 2013). For this reason, controversies and debates existed between researchers and many of them came up with different explanations (Ofori, Briffett, Gang, & Ranasinghe, 2000). In many cases, sustainable and green terms were used interchangeably (Kates, 2010), however sustainable building materials is a much broader term that fulfils more criteria and views than other terms (Sodiq et al., 2019).

The demand for environmentally friendly and green building materials has increased dramatically over the past few years and it is expected to push the building materials industry and construction growth in the next coming years. Besides, the multifaceted nature of SDGs presents big opportunities for building material and product manufacturers to reveal their significant impact on the realization of sustainable development.

According to Secher, Collin, and Linnet (2018a) building materials have a significant impact (direct and indirect) on achieving a variety of goals and targets within sustainable development goals (SDGs), these goals include SDG3, 6, 7, 8, 9, 11, and SDG12. In a similar vein, Secher, Collin, and Linnet (2018b) indicated that building materials and product manufacturers have a direct impact on the realization of 7 of the SDGs including SDG3, SDG6, SDG7, SDG8, SDG9, SDG11, and SDG12.

The reviewed literature showed that the link between building materials and SDGs remains briefly addressed in the literature, thus a more systematic and theoretical analysis is required to fill this gap, which contributes to further research.

Table 2-9 gives definitions of terms for various categories of building materials with the overall aim of achieving sustainable development agenda.

Terminology	Definition	Author (s)	Examples
Sustainable building materials	Are materials produced and sourced locally, they can be reused and recycled, they utilize renewable sources, they use less energy, and they emit fewer greenhouse gases and carbon footprint.	(Patil & Patil, 2017; Sandanasamy et al., 2011; Umar et al., 2016)	Flyash concrete
Green building materials	Are mainly renewable materials or materials which can be reused and recycled and they have a low negative environmental impact throughout their life cycle, they are durable, they use less energy than conventional materials and they can offer a decent indoor environment for the building's occupants	(Cai & Sun, 2014; D & M S, 2018; Kubba, 2017; Spiegel & Meadows, 2010)	Bamboo flooring
Alternative building materials	Material or combination of materials that use available natural resources instead of conventional non-green resources to enhance the inefficient consumption of energy and supplies and to achieve sustainability in buildings.	(Reddy & Jagadish, 2003; Z. Zhang, Wong, Arulrajah, & Horpibulsuk, 2018)	Geopolymer brick
Local building materials	Are materials that can be found locally in a certain geographical location, they are affordable, minimally processed and inherently low carbon	(Morel, Mesbah, Oggero, & Walker, 2001; Ugochukwu & Chioma, 2015; L. Zhu et al., 2009)	Mud and lime
Environmentally friendly/ safe construction materials	Are Healthy materials that make optimal use of resources, produce minimum waste, and they do not release toxic substances throughout their production and use phases, thus they are safe for people and the environment	(Januševičius, Mažuolis, & Butkus, 2016; Kubba, 2010; Petrović, Vale, Zari, & Petrović, 2017a)	Straw-bale
Energy-efficient building materials	Are energy-saving materials which have highly efficient thermal insulating properties, thus reduce the heat gain and heat loss and optimize the thermal performance of the building.	(Aditya et al., 2017)	Insulated concrete form
Low embodied energy building materials	Are Materials extracted and manufactured through low-density industrial processes, while low energy consumed throughout their production phase.	(Azari & Abbasabadi, 2018b; Cabeza et al., 2013)	Stabilized Earth Brick
Advanced building materials	Are economically sustainable materials designed to improved technical properties or environmental qualities compared to the vernacular materials used to serve the same tasks. Thus, they have the capability to increase productivity, decreasing construction time and positively impacting the environment.	(Casini, 2019)	Fibre-reinforced concrete
Durable building materials	Are materials capable to perform their desired functions during a specific period under defined outdoor and indoor climatic conditions and construction of assembly	(Bai, 2016)	Steel
Responsibly sourced building materials	Are materials derived from known, renewable or recycled, legal and well-managed sources	(Attia, 2018)	Wood from sustainably managed forests

Table 2-9: Definitions of terms for various categories of building materials

2.3.3.1 Goal 1: End poverty in all its forms everywhere

The high rates of urbanization and population growth over the past few years have been associated with an enormous demand for building and infrastructure development (Ahmad, Zhao, & Li, 2019) which resulted in shortage and high cost of residential units, high rents, and poor urban living environment (Ugochukwu & Chioma, 2015). Furthermore, the high cost of building materials is a serious challenge affecting against delivery of affordable homes, and public infrastructure and basic services for low-income people, especially in rural communities. In this regard, local building materials (e.g. wood, sand, gravel, clay, lime, etc.) can have a reinforcing contribution on ending some forms of poverty as well as reducing the impact of buildings on the environment.

The utilization of local building materials can cut the construction cost to its barest minimum by about 60% (Ugochukwu & Chioma, 2015), enable low-income people to get access to decent housing at affordable cost with local technology while contributing to the reduction of poverty and building resilient local community, which reduce the local people exposure and vulnerability to the extreme external environmental disasters (Celentano, Escamilla, Göswein, & Habert, 2019). Accordingly, locally produced building materials can participate indirectly to achieve targets No. 1.4 (ensuring equal rights to economic resources, basic services, ownership and control over land and other forms of property) and 1.5 (reducing the exposure and vulnerability to climate-related extreme events) of this goal.

On the other hand, the use of green, advanced, and energy-efficient building materials may have a contradiction with SDG 1 and its related targets due to their initial high cost. Also, a large number of building materials (including local materials) were identified to contain some form of toxicity (Isnin, Ahmad, & Yahya, 2013). These toxic chemicals often have severe consequences on human health (SDG 3), which in return impacts poverty levels. Therefore, applying inexpensive local sustainable techniques to produce local materials that are affordable, durable, environmentally friendly and extracted sustainably can enable the achievement of this goal without hindering the achievement of other goals.

2.3.3.2 Goal 3: Ensure healthy lives and promote well-being

The link between building/ materials and human health is increasingly recognized. Approximately, 1 in 4 of the total universal deaths is assigned to environmental risk factors (Corvalán & Üstün, 2006). People spent more than 90% of their time in enclosed spaces (Building 2030, 2017), and accordingly indoor air typically responsible for over

90% of human exposure to pollutants (Hoisington et al., 2017). If they selected well, the materials of the building can play a major role in offering a healthy indoor environment and promoting well-being for all at all levels. On the contrary, hazardous materials (e.g. asbestos, formaldehyde, polychlorinated biphenyls (PCBs), mercury and lead-based paint) have been found in several construction materials (e.g. insulation, cement, coatings, roofing and flooring materials) and they have the potential to damage health and cause serious diseases, reduced growth, and could create what is known as a sick building syndrome (J. T. Kim & Yu, 2014; Passarelli, 2009; Petrovic´, Vale, & Zari, 2017; Y. Sun et al., 2019; World Health Organization (WHO), 2016b).

Additionally, less often discussed but equally significant is the relation between the quality of building materials and psychological health. People living in a better quality building have fewer mental issues, including reduced anxiety and depression (Hoisington et al., 2017). Hence, quality materials that bring warmth and an appropriate atmosphere to the space are of key importance.

On the other hand, environmentally friendly, green, responsibly sourced, and alternative building materials have a direct contribution to provide healthier indoor zones while enhancing the quality of the built environment (Bragança et al., 2010; Cai & Sun, 2014; D & M S, 2018; Huberman & Pearlmutter, 2008; Kubba, 2010; Patil & Patil, 2017; Sandanasamy et al., 2011; Spiegel & Meadows, 2010). Promoting the use of these materials can prevent the users of the building from diseases of long duration and low progression (non-communicable-or chronic-diseases) like lung diseases, cancer, damage to the liver and central nervous system, which associated with hazardous chemicals emitted into the air from some building materials (Bartzis et al., 2008; FUCIC, 2012; Y. M. Kim, Harrad, & Harrison, 2001; Xu Zhang, Cao, Wei, & Zhang, 2018).

2.3.3.3 Goal 4: Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all

Looking closely at target 4.7 of this goal (ensure that all learners acquire the knowledge and skills needed to promote sustainable development), introducing the impacts of the various types of building materials on human health and environment, besides presenting their importance to support sustainable development through education systems will be a key to achieve UN 2030 agenda and promote a sustainable lifestyle for the next generation (Schmidt et al., 2017; Sichali & Banda, 2017; Umar et al., 2009). Additionally, applying green building materials in the construction of various educational facilities will give real examples for learners, increase public awareness, and provide safe and healthy environments for people, nevertheless, it will enhance the quality of the education and promote sustainability.

2.3.3.4 Goal 6. Ensure availability and sustainable management of water and sanitation for all

The construction industry consumes a massive amount of natural resources, for instance, natural materials, energy, and water. It is in charge of 16% consumption of global water (Heravi & Abdolvand, 2019). So, the consumption of water in the construction industry has a direct influence on water scarcity. Along these lines, building materials consume water during the extraction and processing of the raw materials, through the production stage and throughout the construction of the building. Therefore, increasing the use of green building materials and environmentally safe construction materials can reduce the embodied water of construction materials and increase water efficiency for overall sustainable development (Abd El-Hameed, 2018; Das, Bera, & Moulick, 2015). For instance, up to a 20% reduction in water can be achieved by using fly ash as a partial substitution of Portland cement in concrete (Chandra & Bendapudi, 2011).

On the other hand, many construction materials (e.g. plumbing pipes, roofing materials, paints,) produce chemical hazards (e.g. copper, lead and cadmium) when they have direct contact with water through treatment, storage and distribution. These chemicals can be released from non-sustainable materials after putting in place (e.g. polymeric and elastomeric compounds from plastic fittings or tank linings) or due to the longer contact with water (e.g. soft water can increase metal pipes corrosion whilst hard water can cause scaling) (World health organization, 2010). Therefore, the selection of appropriate materials (including green, alternative, environmentally safe, and responsibly sourced building materials) can reduce pollution, minimize the release of hazardous chemicals and afterwards improve the quality of water (Bardhan, 2011; Sheth, 2017).

2.3.3.5 Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all

Globally, around 48% of the energy is consumed in the construction and operation of buildings (as embodied and operating energy) (Dixit, 2019). Nevertheless, building materials consume energy in every stage during their lifetime starting from the raw material extraction, manufacturing phase, transportation of materials to the project site, the installation and assembly of building materials, energy used for materials maintenance during building use, and the energy used for demolition and transportation of the materials to the landfill or recycling site at the end of building lifetime (Huberman & Pearlmutter, 2008; Zabalza Bribián et al., 2011). In some cases, embodied energy can represent 40% or more of the total energy required for a 50 years lifespan building (Chastas et al., 2016; Thormark, 2006).

However, the use of local, green, environmentally friendly, alternative, energy-efficient, durable and low embodied energy building materials reducing the energy used in buildings, improving the global energy efficiency and serving in achieving SDGs (Peter O. Akadiri et al., 2012; Asif et al., 2007; Basbagill et al., 2013; Cai & Sun, 2014; Dodoo et al., 2012; Macaluso, 2010; Mpakati-Gama et al., 2012; S. Ramesh, 2011; Reddy & Jagadish, 2003; Shams et al., 2012; Singh et al., 2015; Thormark, 2006; Venkatarama Reddy, 2009; L. Zhu et al., 2009), for example, 50% reduction in the total embodied energy can be achieved in masonry load-bearing buildings when energy-efficient or alternative building materials are used (Reddy & Jagadish, 2003). Furthermore, durable building materials can reduce the embodied energy by approximately 76% (50 years lifetime) (Rauf & Crawford, 2015), while using local building materials can achieve a 215% reduction in embodied energy (Morel et al., 2001).

2.3.3.6 Goal 8: Decent work & economic growth - Promote inclusive and sustainable economic growth, employment and decent work for all

The demand for building materials has been growing dramatically since the 1990s and it is expected to continue developing in the coming few years, determined in particular by the rapid industrialization and urbanization growth and high level of material consumption in developed countries (Liming, 2011). A wide variety of people (skilled and semi-skilled labour force) involved throughout the materials lifecycle from raw materials extraction, production, installation, and maintenance.

Recently, the demand for green and alternative building materials in many countries have been accompanied by employing many people from various disciplines, which reflect the impact of building materials in the promotion of economic growth and employment. Also, innovation in the building materials industry and technologies can lead to higher productivity and better efficiency for the use of raw material resources (WGBC, 2017).

2.3.3.7 Goal 9: Industry, Innovation & Infrastructure - Build resilient infrastructure, promote sustainable industrialization and foster innovation

The development of reliable, sustainable and resilient infrastructure is connected directly by using green, advanced, durable, alternative, energy-efficient, low embodied energy, environmentally safe, and responsibly-sourced building materials for the construction of these facilities (Hossain, 2015; Pour-Ghaz, 2013). Their application in the construction of various infrastructures will ensure the quality and the durability of infrastructure (Balasbaneh, Bin Marsono, & Gohari, 2019; Schlangen & Sangadji, 2013; H. C. Wu, 2006) while participating in the development of clean, environmentally friendly and resilient infrastructure. The innovation in the building materials industry will upgrade the development of adaptable, cost-effective and green infrastructure which can face the global challenges of climate change and future risks.

On the other hand, locally available materials like wood, stone, lime, and mud have been replaced by modern construction materials such as steel and cement due to durability concerns. Although modern building materials are durable, they are costly, energy-intensive and harmful to health and well-being. Therefore, buildings structured with the main use of local building materials and well-selected modern construction materials will upgrade the creation of durable and environmentally sound infrastructure (Leo Samuel, Dharmasastha, Shiva Nagendra, & Maiya, 2017).

2.3.3.8 Goal 11: Sustainable Cities & Communities - Make cities inclusive, safe, resilient and sustainable

By 2050, it is expected that 70 % of the world's population will live in cities (B. N. Silva et al., 2018; United Nation-UN, 2014) with an expected increase of the urban residents in the developing world from 2.7 to 5.1 billion between 2011 until 2050 (J, 2015). This predicted growth is supposed to create several sustainability challenges, communally on infrastructure and the environment (Akande, Cabral, Gomes, & Casteleyn, 2019; Bibri & Krogstie, 2017; J. Han et al., 2017; Steverson & Steverson, 2018). If not properly controlled, the rapid urbanization can enlarge informal housing and poverty, poor waste management, in addition to, poor living conditions in cities. Therefore making green and healthy cities is considered a very important issue to achieve a sustainable future for the world (Balaban & Puppim de Oliveira, 2017; Giles-Corti, Lowe, & Arundel, 2019).

Without a doubt, buildings are the foundations of cities and communities, therefore building materials are key to their long-term sustainability. Using locally available building materials can reduce the construction cost, minimize the negative impacts of the buildings on the environment (Bredenoord, 2017; Kayode & Olusegun, 2013), and ensure access to affordable housing and basic services. Moreover, applying green, alternative, environmentally safe, and responsibly sourced building materials is a key for creating a sustainable community that will support the preservation of natural resources and minimize various environmental impacts associated with material's extraction, transport, production, erection, maintenance, and demolition waste (Port, 2007).

2.3.3.9 Goal 12: Ensure Sustainable Consumption and Production patterns

The building materials industry plays a major role in promoting sustainable public procurement, through supporting the use of green, alternative, environmentally safe and responsibly sourced building materials for various construction practices to minimize the environmental impacts, and by encouraging the use of environmental assessments tools to evaluate their environmental impacts throughout their lifespan. Local building materials produced from local responsibly supplies achieve efficient utilization of natural resources. Building materials with green features are considered ecological, non-hazardous, non-polluting and non-radioactive materials (Cai & Sun, 2014). The use of these materials will achieve a healthy environment for human and minimize the negative effect of building on the built environment. Green Building materials have a major role to play in reducing waste through recycling, reuse and by using the cradle to grave approach (Kralj & Markič, 2008; Ng & Chau, 2015). Furthermore, the utilization of durable building materials is key to sustainable consumption, as their use gives precedence to minimizing the amount of materials resources employed and waste produced.

On the other hand, the effective use of building materials is continually evaluated by various environmental assessment tools to ensure the achievement of sustainability in buildings (J. Park, Yoon, & Kim, 2017), while the use of green building materials has already encouraged companies and construction stakeholders to implement sustainability in various projects all over the world.

2.3.3.10 Goal 13: Take urgent action to combat climate change and its impacts

The risks of extreme weather events are expected to grow as a result of climate change, increasing urbanisation and increased needs for resources in urban areas (Andersson-sköld et al., 2015). However, building materials have a huge capability to mitigate the impact of buildings in the global greenhouse gases emissions and other climate-related hazards through the use of energy-efficient, green, environmentally friendly and alternative building materials (B. Huang et al., 2018; Sagheb et al., 2011). To limit these negative impacts, various environmental assessment methods and tools have been created and used to measure all the inputs and outputs of building materials throughout their lifetime (Najjar, Figueiredo, Palumbo, & Haddad, 2017) and many countries integrated these tools into their national policies and strategies (Klijn-Chevalerias & Javed, 2017). Supporting and encouraging the use of these tools and strategies all over the world, can occur great achievement regarding the SDGs.

2.3.3.11 Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Although most of the built environment is located on land, its impacts move to oceans. The built environment and building materials within the coastal watershed have indirect impacts on the sustainability of oceans and marine resources and they can form a permanent source of pollutants, as rainwater passes through the materials of the roofs, facades, and roadways and enters the nearby rivers and seas. Hazardous construction materials (e.g. metal with high zinc content and copper) can cause serious persistent toxicity and bioaccumulation to the marine environment, animals, and plants. Therefore, the use of alternative, green, environmentally safe, and responsibly sourced building materials protect the ecosystem habitats and achieve the related sustainability targets (Perkins and Will Architects, 2016; Petrović, Vale, Zari, & Zari, 2017).

2.3.3.12 Goal 15: Life on land - Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss

The number of buildings and cities on land is rapidly increasing, and thus biodiversity and ecosystems are under intense pressure due to this event. The production and processing of building materials have an indirect impact on biodiversity, the extraction of building materials through mining and quarrying can be altered or even destroyed the natural habitats and species in the quarrying sites (Sahu & Dash, 2011). The above operations require large quantities of water and energy, and they have the potential of generating wastes and pollutants (Fugiel, Burchart-Korol, Czaplicka-Kolarz, & Smoliński, 2017). Also, promoting the application of local building materials may have negative impacts on coastal ecosystems from which the building materials are removed, and on their preservation and restoration. Therefore, promoting the use of green (renewable and recyclable), and responsibly sourced building materials is a key element to achieve sustainability and ensuring better conservation of natural resources as well as it can play a major role to combat desertification and restore degraded land and soil. The utilization of safe and efficient technologies during the extraction and processing of building materials consider an essential task to mitigate their environmental impact (Bloodworth, Scott, & McEvoy, 2009). Also, the encouraging use of responsibly sourced building materials and recycling approach can have a major role to preserve biodiversity and natural habitats (Opoku, 2019).

2.3.3.13 Goal 17: Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

The innovation in the building materials industry will lead to a significant process to strengthen the partnership between the various construction stakeholders, in order to support the achievement of sustainable development goals in all countries. Nevertheless, numerous local and private programs and training have been established in many countries to assist and encourage the implementation of green building materials by sharing knowledge, experiences and professional practice (Nußholz, Nygaard Rasmussen, & Milios, 2019).

2.4 Contemporary Optimization Techniques

2.4.1 Background concept and process

Optimization can be defined as the process aimed to find the best solutions for a specific problem through analysing the performance of certain objects, systems or structures to make their use as effective as possible (maximizing or minimizing some function relative to some set). The optimization process starts by creating a model to describe a specific problem under investigation. Normally, the model is composed of variables, constraints and objective functions. The variables are the parameters that will be used to determine the efficiency of the systems and they are largely varied during the optimization process, while the constraints represent some functional interactions between the design variables and the other parameters. However, mathematical approaches are typically used to model and evaluate particular measures to find the best possible solutions for the given problem (AL-HOMOUD, 1997).

Numerous algorithms can be used to solve a large variety of optimization problems, thus the choice of the suitable one depends on the nature of the problem and on the number of variables that need to be examined (Kheiri, 2018). In the past few years, many nature-inspired optimization techniques have been developed such as Evolutionary Algorithms and Swarm Intelligence. Among them, the Genetic Algorithm (GA) which based on Darwin theory of survival is considered the most common tool which has been used in various contemporary optimization approaches. The idea of applying Darwin's theory on optimization tools to solve engineering problems was introduced in the 1950s and 1960s (Mitchell, 1999). The optimization can be divided into two steps: the first step meant at narrowing the range of values and solutions while the second step aimed at defining the optimal solution among the most susceptible variables (Tian et al., 2018).

2.4.3 Multi-criteria Decision-Making Methods (MCDM)

The Multi-criteria Decision-Making Methods is a well-known technique in environmental decision making and it has been used widely in different industrial processes as an assessment tool (Kurda, de Brito, & Silvestre, 2019). The Multi-Criteria Decision-Making methods (MCDM), also known as Multiple-Criteria Decision Analysis (MCDA) are defined as *"a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter"* (Belton & J Stewart, 2002). In general, the methods are intended to help decision-makers in making choices taking into consideration several criteria (objectives). They are very practical when a range of criteria must be examined simultaneously (Jahan & Edwards, 2013). According to Gilani (2020), the MCDM can be characterized regarding their problem-solving technique or based on their mathematical nature. The first group include the value-based methods, outranking methods and choosing by advantages methods. The second group include multi-objective decision making, multi-attribute decision making, or a combination of both systems. See **Figure 2-16**

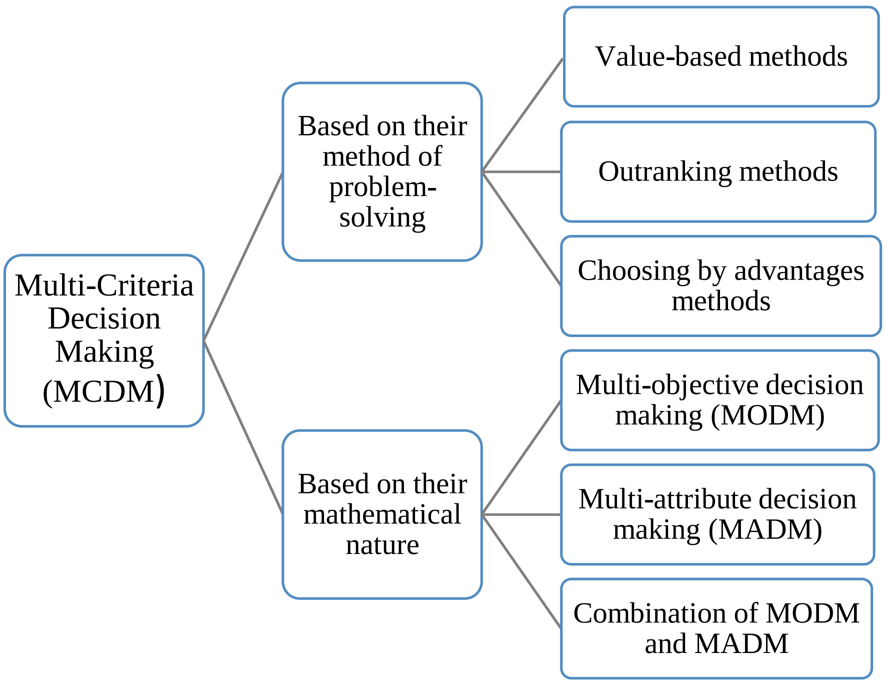


Figure 2-16: Most common categorization of MCDM methods

Adapted from (Gilani, 2020)

The value-based methods are extensively utilized in building design practice and literature; in such systems, numerical scores are structured for each criterion (factor), and afterwards, an aggregation model is used by decision-makers to select the best choice based on the weights of different criteria (factors). Outranking methods use pairwise comparisons to assess the selection of preferences. In these methods, the alternatives would be compared referring to each criterion (factor) and then sum up the preferences and finally find evidence for the selection of one choice over the other. In choosing by advantages methods the factors that make significant differences between alternatives will be selected; the advantages of each alternative will be identified, and then determining the weight of the advantages by making comparison among them, and finally, the decisions are only based on advantages of each alternative.

Multi-objective decision making (MODM) is normally used to achieve several objectives at the same time: minimizing impacts, maximizing efficiency, minimizing cost, maximizing reliability, etc., hence multiple goals and alternatives solutions could be achieved when this method employed. Furthermore, multi-objective optimization presents more realistic results for the examined models and open more challenges for the participants in decision-making developments.

The MODM have been intensively used in the literature for the optimization of four main issues including energy-related concerns (energy consumption), Environmental issues (annual emissions and global warming potential), Life comfort (indoor temperature and humidity), and Cost (life cycle cost & annual energy cost) (Shakouri G., Rahmani, Hosseinzadeh, & Kazemi, 2018). On the other hand, MADM methods, are mostly discrete, involving the selection from a finite number of specified alternatives. According to Rao (2007), these methods demand both inter-and intra-attribute assessments and include appropriate explicit tradeoffs.

In the previous studies, the methods of assigning weights to the assessment criteria can be categorized into three options: subjective method, objective method, and integrated method (Z. S. Chen et al., 2019; Dong, Liu, Liang, Chiclana, & Herrera-Viedma, 2018; Hatefi, 2019). The subjective method is the most commonly used and it is based on the preference of the decision-makers on specific criteria. In the second approach, the weights can be determined based on the objective decision matrix information for alternatives; this includes the TOPSIS-based method, entropy method, and other mathematical programming based methods. Lastly, the integrated method assigns the weights using both subjective and objective decision information. However, there is no agreement as to which method produces more accurate weights.

2.4.4 Building Materials Optimization Approach

The need for evaluating the construction materials has been considered as the main topic in today's research. The optimal material selection is often treated as a multi-criteria decision-making (MCDM) problem where the most appropriate material is to be chosen based on a given set of multiple criteria. As stated previously, the optimization of building materials includes various topics; such as: optimizing their production and ongoing costs, resources utilization, durability properties, energy and water-saving, indoor environmental quality, as well as optimizing the environmental impacts of their use. Undoubtedly, the optimization of building materials is significant to achieve sustainable building. **Figure 2-17** shows a typical framework used to solve a decision making problem for the selection of optimal alternatives.

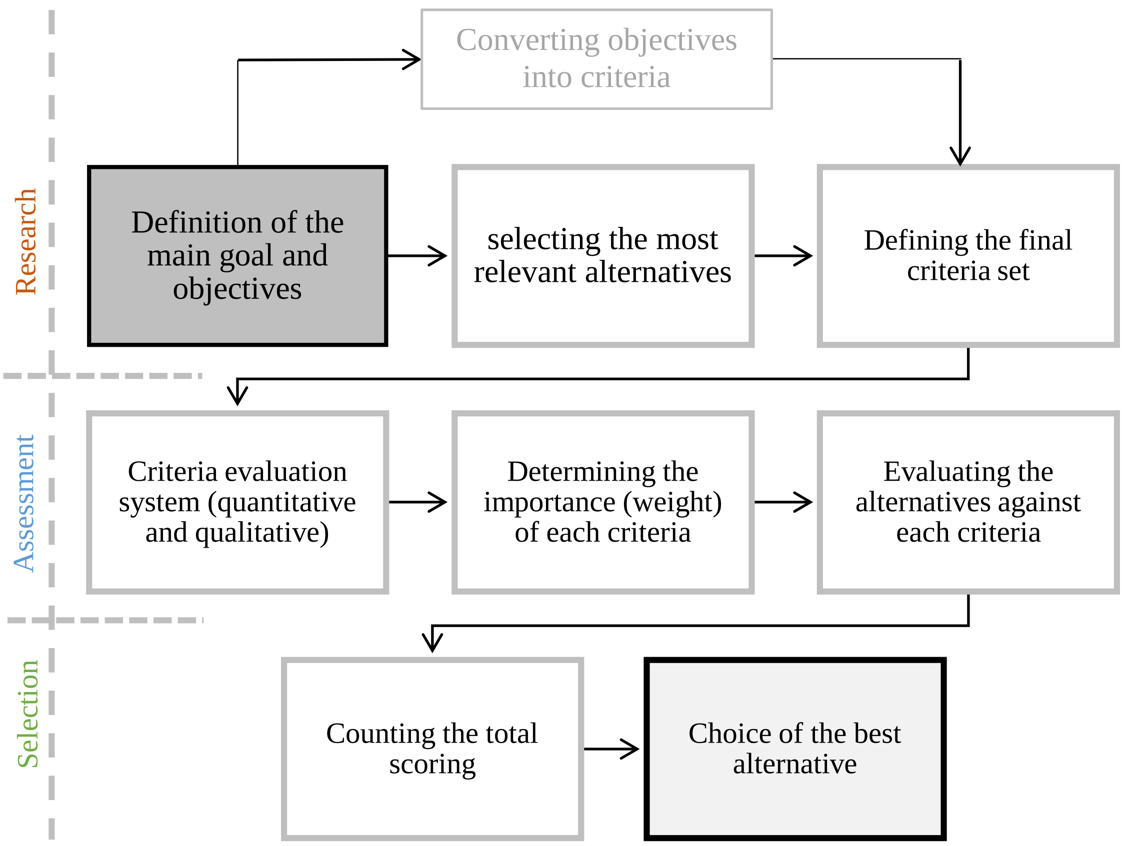


Figure 2-17: Typical steps in multi-criteria optimization methods

The multi-criteria optimization approach has been studied in many examples in the building material sector, for example, it has been used to optimize: insulation options to increase energy efficiency (Amani & Kiaee, 2020; Civic & Vucijak, 2014), conventional or non-conventional concrete mixes (Kurda et al., 2019), high energy efficiency external walls (Baglivo & Congedo, 2016; Baglivo, Congedo, & Fazio, 2014), etc. According to GARBA, OLALEYE, and JIBRIN (2015), several factors must be considered for sustainable material resources optimization include the implementation of prefabricated component systems, utilization of material schedule software, using of standard space product design, reuse and recycling of old building materials in new construction projects, and the use of proper equipment and specification.

It is worth noting that the Analytic Hierarchical Process (AHP) has been found as the most frequently used method among MCDM methods to a material selection problem. However, some researchers concluded that the subjective nature of AHP may cause several defects; the group of decision-makers may not be able to agree on a set of exact weights. Besides, the larger the number of the criteria, the lower the accuracy of the subjective method (Hatefi, 2019). Thus, the need for a coherent, understandable and numerically robust approach to comparing building materials amidst multiple criteria is remaining.

2.5 Chapter Summary

This chapter has explored the literature concerning the relationship between building materials, sustainable development and energy efficiency in line with the objectives set out in chapter one. The chapter identified that green and sustainable phrases have often used interchangeably in the research. The green focuses on people and products while sustainable investigates the impacts of the products on human health and the environment throughout their lifespan. In this thesis, sustainability has been defined as a balanced approach aimed to integrate environmental, economic and social aspects to the benefit of present and future generations. This has been linked to the most agreeable definition of sustainability offered by the Brundtland Commission.

Moreover, the chapter critically reviewed how green and sustainable building materials have the capability to make a significant contribution to a more sustainable planet for humankind. However, the review of the existing literature helps us to define green building materials as renewable materials or materials which can be reused and recycled and they have a low negative environmental impact during their life cycle, they are durable, they use less energy than conventional materials and they can offer a decent indoor environment for the occupants of the buildings.

Furthermore, the chapter reviewed the barriers and challenges affecting the implementation of sustainable building materials in real construction practice and it concluded that there is a common similarity in some barriers revealed from the existing review including the lack of awareness and knowledge, lack of availability of green building materials and tools, the initial and ongoing cost of green materials, time constraint, and lack of legislation and building codes. Additionally, the sustainability criteria for the selection of building materials has been investigated in this chapter.

The relevant literature has identified a various range of economic, technical, social, and environmental criteria affecting the sustainable life cycle of materials. The review of this part proved the necessity of creating a multi-criteria decision-making tool to evaluate and select preferred green building materials based on a wide set of criteria.

Also, the findings showed that embodied energy (EE) and greenhouse gases emissions (GHG) are the main serious indicators in the impact evaluation of building materials in the environment. Thus, the need for applying life cycle assessment methods to evaluate the environmental impacts of building materials as well as their embodied energy share in the total consumed energy is highly recommended to achieve a sustainable building.

On the other hand, the findings of this chapter proved that building materials have a direct and indirect contribution to the achievement of several SDGs and targets. It is found that building materials have a significant role to achieve 13 goals and 25 targets of the United Nations Agenda 2030. The results verified that building materials play an essential role in enhancing well-being, increasing energy and water efficiency, promoting responsible consumption and production, building resilient infrastructure and sustainable cities, and they have a huge capacity to mitigate climate change while accelerating the achievement of Sustainable Development Goals (SDGs). (See Appendix B)

Last but not least, the chapter reviewed the contemporary optimization techniques employed to solve a large variety of engineering problems while the focus was on the multi-criteria optimization methods accustomed to assess the environmental impacts of building materials. Most of these tools have a subjective nature which may not assure the decision is certainly true. Also, it is almost difficult to assign weights when the number of criteria increases because the weights depend on the personal input from a group of experts. Therefore, this conclusion showed the need for a more practical and simple approach to evaluate the sustainability of building materials based on the value of each criterion.

CHAPTER 3: CONVENTIONAL AND ADVANCED BUILDING MATERIALS AND TECHNOLOGIES

September 2021

3. CHAPTER THREE: CONVENTIONAL AND ADVANCED BUILDING MATERIALS AND TECHNOLOGIES

3.1 A review of the state of the art studies of commonly applied building materials and their advancements

The rising concern about the unsustainable consumption of natural resources and related environmental impacts have resulted in producing green products using sustainable manufacturing processes. Recently, there are primary concerns that practically all manufacturers need to address to produce green products including resource consumption, energy consumption, water use, and carbon emissions. In the construction industry, the commonly applied building materials including concrete, steel and aluminium are consuming a great amount of energy and releasing a huge quantity of carbon dioxide during the production process. Thus, the development of new advanced materials and construction techniques as alternatives to contemporary building materials are becoming a challenge towards the transition to a more sustainable industry.

Building materials are used throughout the life cycle of the building, thus they play an important role in enhancing the overall performance of the building and in achieving the goal of sustainable construction. In the past, the cost, performance qualities and aesthetics are the main factors that influence material selections in various construction projects, while the environmental impacts of building materials are not considered as a primary concern. In the last years, building materials are constantly improved with the development of technology to fulfil safety and operational standards. Thus, assessing the environmental impacts of these materials turn out to be an essential task in the design and construction of green buildings. In this regard, two questions need an answer: What environmental impacts are arising from materials production and use? What are the options at the end of their lifetime?

This chapter aimed to give an insight into the commonly used building materials for facades, their practical consideration and environmental impacts, and their sustainable alternatives (low impact building materials). It is intended to help architects and designers to specify and track the most recent sustainable building materials and technologies applied in the construction industry.

3.1.1 Bricks

Bricks are extensively utilized construction material around the globe because they are affordable, durable, simply manufactured, and they have superior strength and thermal properties (Bories, Borredon, Vedrenne, & Vilarem, 2014). They have been used for loadbearing walls and flooring, non-loadbearing external cladding (face bricks), internal structure, and supplementary construction components. Bricks have been expended as one of the main construction materials since 8000 B.C (Torgal & Jalali, 2011). Globally, the annual production of bricks is about 1.83 trillion units and this figure is expecting to increase to 2.76 units by 2027 as a result of globalization and urbanization growth (Bhairappanavar, Liu, & Shakoor, 2021; L. Zhang, 2013). Bricks are traditionally manufactured from clay firing in high-temperature kilns or ordinary Portland cement concrete (does not require high-temperature kilns).

The manufacturing process of fired-clay bricks can be divided into main four stages involving: 1) selection and preparation of the raw clay; 2) mixing and moulding; 3) drying of the fresh brick units; 4) firing of the units in kiln/oven (F. M. Fernandes, 2019). However, this process entails high embodied energy, produces a huge quantity of greenhouse gases, and utilizes a huge quantity of natural resources. For instance, the embodied energy of a common brick can reach a figure of 3.0 MJ/kg and the greenhouse gas emissions about 0.24 $kgCO_2e/kg$ (University of Bath, 2011). Moreover, the increasing demand for fired clay bricks has caused a shortage of natural clay resources in many countries (Bhairappanavar et al., 2021; Lingling, Wei, Tao, & Nanru, 2005).

The concrete bricks on the other hand are manufactured from ordinary Portland cement and aggregate. These types of bricks are prepared from mixed aggregates with cement under pressure in moulds. Concrete bricks are well known for their cost-effectiveness, durability and fire-resistance. However, as cement is the main raw material, a large amount of CO_2 is produced during the manufacturing process (Dawood & Mahmood, 2021). For instance, the production of 1 kg of Portland cement consumes 4.51 MJ of energy and emits 0.74 kg of CO_2. Also, the production of some type of concrete blocks can have an associated embodied carbon of 0.107 $kgCO_2e/kg$ and embodied energy of 0.83 MJ/kg (University of Bath, 2011).

In previous years, the production of bricks is changing towards a sustainable way of manufacturing by integrating pre-consumer and post-consumer wastes in the cementing process rather than using soil and firing in kilns (Gavali & Ralegaonkar, 2020). In this regard, several alternatives have been studied, for instance, fly ash, slags, construction and demolition waste, rice husk ash, bio-briquette ash, sugarcane bagasse ash, wood and cotton sawdust, waste glass sludge, dredged material, the vegetable matter of various compositions and shapes, mine tailings, Kraft pulp production, paper production residue, olive mill solid residue, waste tea, cigarette butts, crumb rubber, solid waste (sludge) and more (Bhairappanavar et al., 2021; Bories et al., 2014; L. Zhang, 2013).

On the other hand, co-occurrence analysis was made to identify core keywords of the published articles regarding the sustainability of bricks. Keywords that identified as building materials or substitute of virgin materials are included, other excluded. The following topics have been searched in the web of science database from 2010 to 2021: ("sustainable brick*" or "eco-friendly brick*" or "sustainable clay-brick*" or "alternative brick*" or "sustainable cement brick*" or "sustainable concrete block*" or "sustainable concrete brick*" or "energy-efficient brick*"). The top five keywords with a high frequency of occurrence include fly-ash, waste, residues, sugarcane bagasse, and rice husk ash (See **Figure 3-1**).

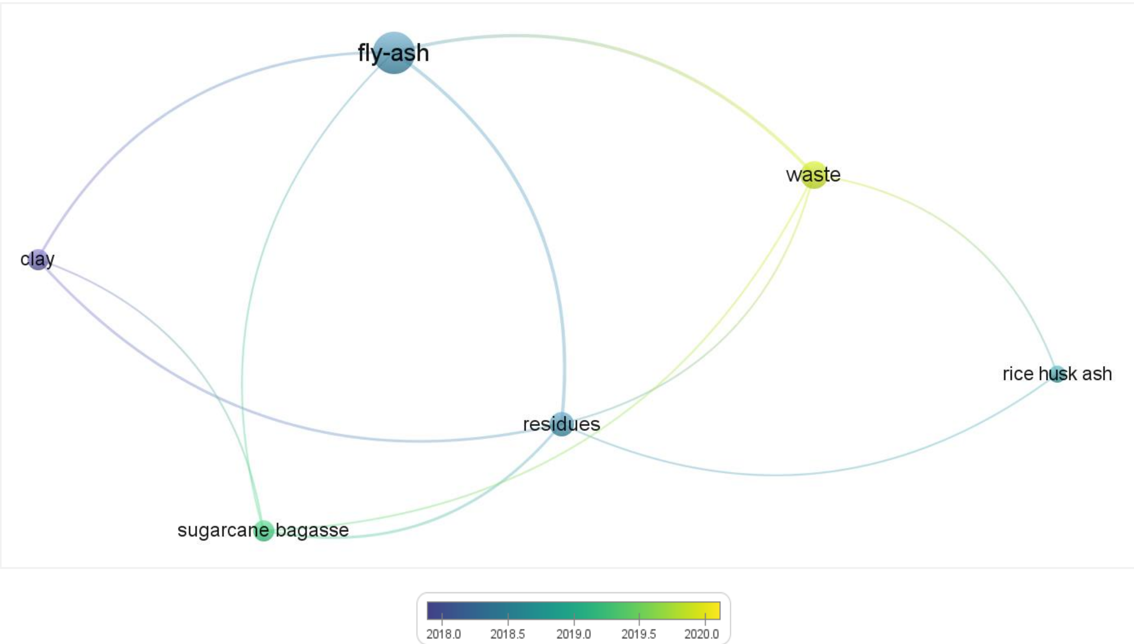


Figure 3-1: The top five commonly examined materials and alternatives to enhance the sustainability of bricks

Note: results from VOSviewer software version 1.6.7.

Most of the commonly studied approaches to creating sustainable and eco-friendly bricks are shown in **Table 3-1**.

Alternative brick type	Optimization Techniques/Methods/Materials	Reference (s)
Clay-sand-rice husk ash mixed bricks.	Mixing clay-sand with different percentages of rice husk ash.	(Görhan & Şimşek, 2013; M. A. Rahman, 1987)
Fired clay bricks with river/ harbour sediments.	Mixing the dredged sediments with natural clay.	(Hamer & Karius, 2002; Lafhaj et al., 2008; Mezencevova, Yeboah, Burns, Kahn, & Kurtis, 2012; Samara, Lafhaj, & Chapiseau, 2009; Y. Xu, Yan, Xu, Ruan, & Wei, 2014)
Granite sawing wastes in the production of ceramic bricks.	Conventional ceramic raw materials and granite sawing wastes were used.	(Menezes, Ferreira, Neves, Lira, & Ferreira, 2005)
Porous and lightweight bricks.	Mixing raw brick-clay with kraft pulp production residues.	(Demir, Baspinar, & Orhan, 2005)
Geopolymer green clay bricks instead of burnt clay brick.	Optimizing the amount of clay and fly ash as precursors (replacing clay with fly ash).	(Abbas, Saleem, Kazmi, & Munir, 2017; Iftikhar et al., 2020; Lingling et al., 2005)
Brick made from municipal solid waste incinerator fly ash.	Replacing the clay with municipal solid waste incinerator fly ash.	(Lin, 2006)
Processed waste tea clay brick.	Adding different ratios of the processed waste tea to the raw-brick clay.	(Demir, 2006)
Concrete block combining limestone dust and wood sawdust/ cotton waste.	Mixing Portland cement with limestone powder wastes and wood sawdust wastes/ cotton waste.	(Algin & Turgut, 2008; Turgut & Murat Algin, 2007)
Bricks from organic pore-forming agents.	Mixing sawdust, tobacco residues, and grass with raw brick clay.	(Demir, 2008)
Lightweight composite brick using crumb rubber.	Mixing cement, sand, and crumb rubber (crumb rubber as a partial replacement of fine aggregates).	(Thakur, Senthil, Sharma, & Singh, 2020; Turgut & Yesilata, 2008)
Porous and lightweight bricks from paper processing residues.	Mixing brick raw materials with paper processing residues waste at different proportions.	(Sutcu & Akkurt, 2009)
Clay brick with treated river sediments.	Substituting the quartz sand by treated river sediments.	(Samara et al., 2009)
Light-Weight Fired Clay Bricks.	Recycling cigarette butts into fired clay bricks.	(Kadir, Mohajerani, Roddick, & Buckeridge, 2009)
Lightweight bricks manufactured from water treatment sludge and rice husks.	Mixing dried water treatment sludge and rice husk.	(Chiang, Chou, Hua, Chien, & Cheeseman, 2009)
Porous fired clay bricks.	Mixing vegetable matter of various compositions and shapes (wheat straw, corn cob, several seeds (rape, maize, wheat and sunflower) with raw brick clay.	(Saiah, Perrin, & Rigal, 2010)
Paper sludge- palm oil fuel ash brick.	Incorporating paper sludge and palm oil fuel ash into cement.	(Ismail, Ismail, Lau, Muhammad, & Majid, 2010)
Eco-friendly construction bricks from hematite/slate tailings.	Tailings, clay and fly ash were added to the raw materials to improve the brick quality.	(Y. Chen, Zhang, Chen, Zhao, & Bao, 2011; X. Kang, Gan, Chen, & Zhang, 2021)
Lightweight clay brick from olive mill solid residue.	Adding olive mill solid residue to the clay.	(De La Casa, Romero, Jiménez, & Castro, 2012; La Rubia-García, Yebra-Rodríguez, Eliche-Quesada, Corpas-Iglesias, & López-Galindo, 2012)

Alternative brick type	Optimization Techniques/Methods/Materials	Reference (s)
Eco-friendly bricks from copper mine tailings.	Mixing the tailings with an alkaline solution.	(Ahmari & Zhang, 2012)
Waste Crete Bricks.	Mixing recycled paper mills waste and cotton waste with a fixed content of Portland cement.	(Rajput, Bhagade, Raut, Ralegaonkar, & Mandavgane, 2012)
Lightweight bricks from recycled paper mill waste.	Combining cement with recycled paper mill waste.	(Raut, Sedmake, Dhunde, Ralegaonkar, & Mandavgane, 2012)
Building blocks by partially replacing cement with bottom ash.	Using bottom ash from plant biomass to substitute cement in building blocks.	(Carrasco, Cruz, Terrados, Corpas, & Pérez, 2014)
Masonry blocks containing palm oil fuel ash.	Replacing cement with palm oil fuel ash.	(M. E. Rahman, Boon, Muntohar, Hashem Tanim, & Pakrashi, 2014)
Lightweight concrete brick (block).	Replacing Portland cement with wood fibre waste, rice husk ash, and limestone powder waste.	(Torkaman, Ashori, & Sadr Momtazi, 2014)
Lightweight Bagasse Ash Bricks.	Combining sugarcane bagasse ash, quarry dust, and Lime.	(Madurwar, Mandavgane, & Ralegaonkar, 2015)
Bricks from bio-briquette ash.	Adding bio-briquette ash as a partial replacement of sand while keeping the cement percentage constant.	(Sakhare & Ralegaonkar, 2016)
Burnt clay bricks incorporating waste glass sludge.	Mixing of clay and waste glass sludge.	(S. M. S. Kazmi, Abbas, Nehdi, Saleem, & Munir, 2017)
Alkali-activated bricks made from industrial wastes.	Bricks were cast by using co-fired blended ash and stone dust with an alkali-activator.	(Gavali & Ralegaonkar, 2020)
Slu-brick from solid waste (sludge).	Replacing clay with sludge.	(Patel et al., 2020)
Sustainable concrete bricks instead of conventional concrete bricks.	Adding Nano-silica, glass powder and steel slag powder for different concrete bricks mix.	(Dawood & Mahmood, 2021)
Eco-friendly dredged material-cement bricks.	Mixing of sand, sieved from the dredged material and cement.	(Bhairappanavar et al., 2021)

Table 3-1: The recent materials and methods applied to creating sustainable and eco-friendly bricks

3.1.2 Concrete and Cement Products

Concrete is the most common construction material which has extensive applications in the construction industry. It has a long life expectancy, high strength, and good thermal and mechanical properties (S. Khan, Maheshwari, Aglave, & Arora, 2019). Despite having various advantages, concrete and cement products are widely known as building materials with one of the greatest negative impacts in the construction industry. Concrete is the most consumed material after water. It is basically consisting of cement, gravel, sand, water and additives (Teixeira, Mateus, Camões, Bragança, & Branco, 2016). The production of cement uses a large number of natural resources, energy, and produces a huge amount of carbon emissions. Portland cement is the most used cement type in concrete production which mainly compromise clinker. Clinker production requires considerable thermal energy quantities and CO_2 emissions (Galvez-Martos & Schoenberger, 2014). About 60% of these emissions originate during the decarbonisation of limestone in the clinkering process. Also, aggregates play a core role as they account for about 80% to 85% of a typical concrete mixture (Collivignarelli et al., 2020).

In 2019, the total production of aggregates and cement was estimated at 48.3 billion tonnes and 4.1 billion tonnes, respectively (de Brito & Kurda, 2021). The expected demand for cement is assumed to be 6 billion tonnes by 2025 (see **Figure 3-2**). These figures arise a question about the availability of these materials and their environmental impacts in the coming years.

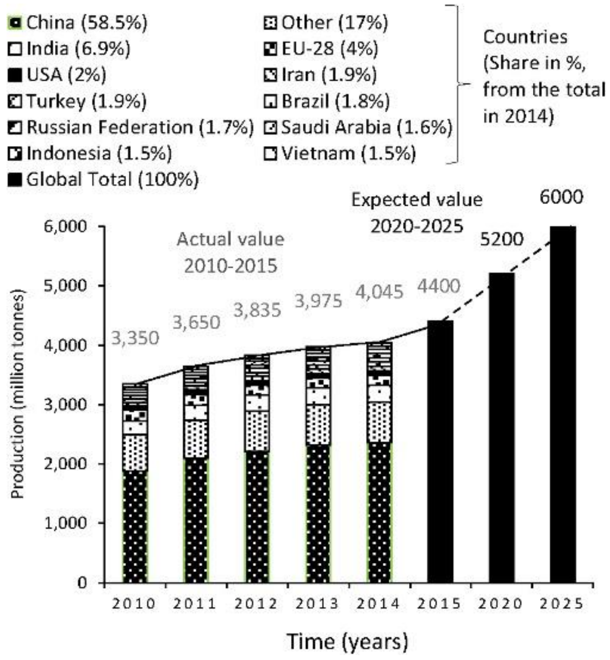


Figure 3-2: Global cement production in the top 10 countries
Adapted from (Kurda, Silvestre, de Brito, & Ahmed, 2018)

The cement production is responsible for producing approximately 7% of the total CO_2 emissions worldwide (Ríos-Parada, Jiménez-Quero, Valdez-Tamez, & Montes-García, 2017). The production of cement is the most important factor that affects the embodied energy of concrete. According to O'Brien et al. (2009), approximately 70% of the concrete embodied energy has resulted from cement, while transportation and aggregates are responsible for 17-25% and 3-5%, respectively. Furthermore, it is estimated that the average global warming potential (GWP) of 1 kg aggregate is 0.0123 kg CO_2 eq and 981 kg CO_2 eq for cement (de Brito & Kurda, 2021).

To reduce the negative impacts of concrete production, several methods have been developed to use products that have lower environmental impacts than cement and natural aggregates. The majority of these studies have been advanced with the use of materials introduced as co-products and by-products in industrial processes from several sectors. These materials have been utilized as substitutes for cement to produce materials that have similar characteristics to the raw materials used to produce typical concrete. The replacement of Portland cement by supplementary cementitious materials (SCMs) is a widely adopted industrial practice, especially for, fly ash (type F coal FA), silica fume (SF), and blast furnace ground slag (BFGS). The most examined materials and alternatives found in the literature in the field of sustainable concrete include fly-ash, silica fume, recycled aggregate (recycled concrete aggregate), ground granulated blast furnace slag, palm oil fuel ash, metakaolin, and geopolymer concrete (see **Figure 3-3**).

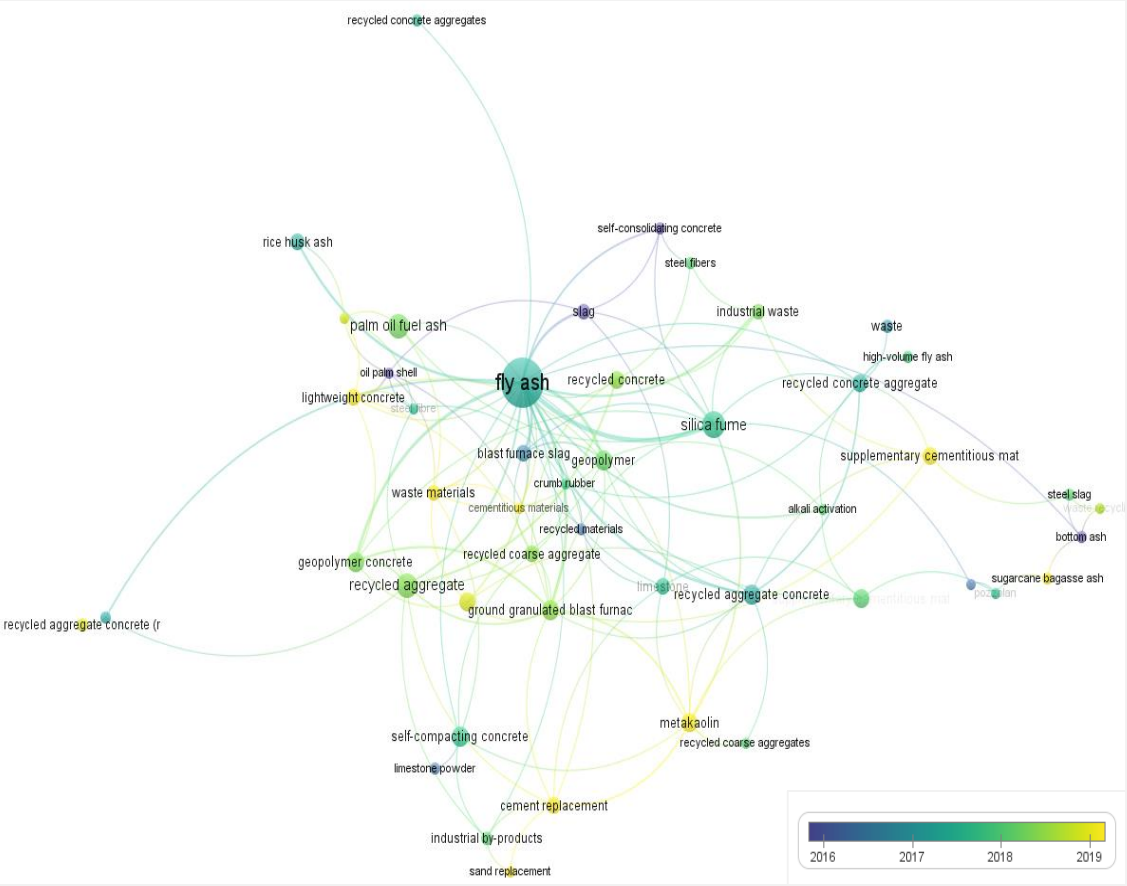


Figure 3-3: The most examined materials and alternatives found in the literature in the field of sustainable concrete

Note: results from VOSviewer software version 1.6.7. The searched topics: ("sustainable concrete" or "eco-friendly concrete" or "Energy-efficient concrete" or "green concrete" or "low carbon concrete"); Timespan: (2010-2021).

Moreover, several advantages have been seen by using the construction and demolition (C&D) waste as a recycled aggregate to promote sustainability in concrete (Behera, Bhattacharyya, Minocha, Deoliya, & Maiti, 2014; Jayasuriya, Shibata, Chen, & Adams, 2021). In this regard, the study of recycled concrete aggregate (RCA) as an alternative material to replace natural aggregate has been extensively reviewed (Kurda & Brito, 2019; Mistri et al., 2021). Also, the recycled masonry aggregate (RMA) (J. Hu, Wang, & Gaunt, 2013; R. V. Silva, De Brito, & Dhir, 2015), contaminated construction and demolition waste (R. V. Silva, de Brito, & Dhir, 2019), mixed recycled aggregate (MRA) (Martínez-Lage, Vázquez-Burgo, & Velay-Lizancos, 2020), agricultural wastes and aquaculture farming (Luhar, Cheng, & Luhar, 2019; Prusty, Patro, & Basarkar, 2016), industrial wastes (Kaish, Odimegwu, Zakaria, & Abood, 2021), municipal wastes (X. Li et al., 2020), and other types of aggregates have been used.

Table 3-2 shows the most commonly studied supplementary cementitious materials (SCMs) for producing concrete products with low environmental impacts

Supplementary cementitious materials (SCMs)	**Optimization methods/Strategies/Materials**	**Reference (s)**
Agricultural wastes and aquaculture farming (AWAF)		
Rice husk ash	Rice husk ash (RHA) is a highly-reactive pozzolanic material and can replace up to 20% of Portland cement in concrete mix designs.	(Gursel, Maryman, & Ostertag, 2016; R. Khan et al., 2012; Moayedi, Aghel, Abdullahi, Nguyen, & Safuan A Rashid, 2019)
Palm oil fuel ash	A 25% replacement level exhibited high compressive and splitting tensile strength.	(Al-Mulali, Awang, Abdul Khalil, & Aljoumaily, 2015; Aprianti S, 2017; Awang, Al-Mulali, Abdul Khalil, & Aljoumaily, 2014)
Corn cob ash	Up to 8%, CCA substitution is adequate where the blended cement is to be used for structural concrete.	(Adesanya & Raheem, 2009; Suwanmaneechot, Nochaiya, & Julphunthong, 2015)
Baggase ash	The substitution of 30% baggase ash is acceptable for producing high-strength concrete.	(Frías, Villar, & Savastano, 2011; Ríos-Parada et al., 2017; Rukzon & Chindaprasirt, 2012)
Straw ash	The straw ash is an effective mineral admixture in concrete when the replacement ratio is 10%.	(Memon, Wahid, Khan, Tanoli, & Bimaganbetova, 2018; Q. Zhang, Li, Xu, & Lun, 2019)
Leaf ashes	Cement could be replaced with bamboo leaf ash to 15% with a little compromise in strength and durability characteristics.	(Kolawole & Olusola, 2015; S.A, 2014)
Forest waste bottom ashes (biomass ashes)	The basic strength was maintained with 10-15% replacement with forest waste bottom ash.	(Demis, Tapali, & Papadakis, 2014; Garcia & Sousa-Coutinho, 2013; Rajamma et al., 2009)
Wood ashes	The material was found to be satisfactory and possible for low-quality concrete.	(Ayobami, 2021; Berra, Mangialardi, & Paolini, 2015)

Agricultural wastes and aquaculture farming (AWAF)	Optimization methods/Strategies/Materials	Reference (s)
Olive waste ash	The use of biomass fly ash as a filler in self-compacting concrete.	(Al-Akhras, Al-Akhras, & Attom, 2009; Cuenca, Rodríguez, Martín-Morales, Sánchez-Roldán, & Zamorano, 2013)
Tobacco waste ash	It is possible to replace 10% of the cement with tobacco waste ash.	(Celikten & Canbaz, 2017; Moreno et al., 2018)
Elephant grass ash	The use of 20% cement replacement was considered adequate.	(Cordeiro & Sales, 2015)
Banana leaves ashes	Concrete with 10% banana leaves ash were satisfactorily cast.	(Kanning, Portella, Bragança, Bonato, & Dos Santos, 2014)
Seashells waste	Greater replacement levels of up to 25%–50% enhanced concrete absorption and porosity while reduced workability.	(Bamigboye et al., 2021; Lertwattanaruk, Makul, & Siripattarapravat, 2012; Olutoge, Okeyinka, Olaniyan, & Oyo, 2012)
Oyster shell powder	The sample with 10% oyster shell powder was close to those of the original concrete mixes without addition.	(Zhong, Zhou, Chan, & Yu, 2012)
Periwinkle shell ash	10% periwinkle shell ash content is adequate as cement substitution for structural concrete.	(A.A. & K.O., 2013; Olusola & Umoh, 2012)
Eggshell powder	The optimum percentage of eggshell powder as a partial cement replacement is 15%.	(Y. Y. Tan, Doh, & Chin, 2018)
Industrial wastes as SCM	**Optimization methods/Strategies/Materials**	**Reference (s)**
Fly ash (coal fly ash and coal bottom ash)	The integration of fly ash showed the possibility of making high strength concrete while decreased the environmental impact, cost, use of landfill space and natural resources extraction.	(Dandautiya & Singh, 2019; K. Kim, Shin, & Cha, 2013; Kurda, Silvestre, & de Brito, 2018; Kurda, Silvestre, de Brito, et al., 2018; Mangi et al., 2018; Singhal, Nagar, & Agrawal, 2020; Teara & Shu Ing, 2020; Teixeira et al., 2016)
Industrial slags (ground granulated blast furnace slag)	The use of GGBFS as a partial replacement for cement in concrete mixtures can decrease energy consumption and reduce greenhouse gas emissions.	(Gholampour & Ozbakkaloglu, 2017; Kandiri, Mohammadi Golafshani, & Behnood, 2020; Özbay, Erdemir, & Durmuş, 2016; Tait & Cheung, 2016)
Silica fume (SF)	5% silica fume content in the recycled aggregate concrete is more appropriate to enhance compressive strength.	(Dilbas, Şimşek, & Çakir, 2014; M. Jalal, Pouladkhan, Harandi, & Jafari, 2015; Pedro, de Brito, & Evangelista, 2017)
Artificial pozzolans (calcined clays (metakaolin), ceramic residues, sedimentary rocks containing clay minerals, burned bauxites)	Different percentages of Artificial pozzolans can be utilized as a partial replacement of cement.	(L. G. Li, Zhuo, Zhu, Chen, & Kwan, 2019; Schulze & Rickert, 2019; Vejmelková et al., 2018)
Natural pozzolans (volcanic glasses, pumice and pumicite, volcanic tuffs/zeolites, and opal and diatomaceous earth)	Increasing the incorporation ratio of natural pozzolans can significantly decrease the concrete cost.	(Lemougna et al., 2018; J. Li, Zhang, Li, & Monteiro, 2019; Raggiotti, Positieri, & Oshiro, 2018; Ulusu, Aruntas, & Gencel, 2016)

Industrial wastes as SCM	Optimization methods/Strategies/Materials	Reference (s)
Natural pozzolans (volcanic glasses, pumice and pumicite, volcanic tuffs/zeolites, and opal and diatomaceous earth)	Increasing the incorporation ratio of natural pozzolans can significantly decrease the concrete cost.	(Lemougna et al., 2018; J. Li et al., 2019; Raggiotti et al., 2018; Ulusu et al., 2016)
Municipal wastes as SCM	**Optimization methods/Strategies/Materials**	**Reference (s)**
Glass powder	Concrete made with 20% glass powder replacement presented increases in 91-day compressive strength (7%).	(F.R, B.H, Choong, & O.Q, 2016; Omran & Tagnit-Hamou, 2016; S. B. Park, Lee, & Kim, 2004)
Sludge ashes (sewage sludge ash, sludge wastewater sludge ash, paper sludge, granite waste sludge, galvanic sludge, glass waste sludge, paint sludge, and contaminated arsenic sludge)	Different percentages of these wastes can be used as a partial replacement for cement.	(Al-Hamaiedeh & Khushefati, 2013; Avci, Ghorbanpoor, Topcu, & Nurbas, 2017; Baeza-Brotons, Garcés, Payá, & Saval, 2014; N. K. Bui, Satomi, & Takahashi, 2019; Jihwan Kim et al., 2014; Luz, Rocha, Cheriaf, & Pera, 2009; Lynn, Dhir, Ghataora, & West, 2015; Nakic, 2018; Roy et al., 2018)

Table 3-2: The most commonly used supplementary cementitious materials (SCMs) for producing lower impact concrete products

Besides the cement and virgin aggregate, concrete production is consuming a huge amount of water. According to Silva et al. (2010), approximately 150 litres of water are required for the production of each cubic meter of concrete. Therefore, using other types of water for concrete mixing is required to reduce water consumption; for instance the use of seawater (Younis, Ebead, Suraneni, & Nanni, 2018); water recovered from discarded ready-mix concrete (Xuan, Poon, & Zheng, 2018); wastewater (from sewage, industry, and other grey water) (Ghrair et al., 2018; Saxena & Tembhurkar, 2018). Similarly, the steel bars in concrete have been replaced with non-conventional bars to reduce the overall environmental impacts of concrete products, for instance, bamboo fibre (N. Rahman et al., 2017), and polypropylene fibres (Tuladhar & Yin, 2019).

Recently several low-environmental impact concrete products have been used in building's façade such as hemp-lime concrete or simply "hempcrete" (Ingrao et al., 2015; Maalouf et al., 2018; Sassoni, Manzi, Motori, Montecchi, & Canti, 2014), Fibre Reinforced Concrete (K. T. Q. Nguyen et al., 2020), Foamed Concrete (S. N. Shah, Mo, Yap, Yang, & Ling, 2021), and Autoclaved Aerated Concrete-AAC (Ricciotti et al., 2020), and numerous Concrete Blocks made with waste aggregate and other agriculture and industrial wastes.

3.1.3 Metal and steel products

There are a variety of metals used in the construction of buildings worldwide. For instance, Aluminum, Titanium, Copper, Zinc, and Iron are all metals that have been known for their long life span, their ability to be reused and recycled, and their durability. Steel, on the other hand, which is an alloy of iron is also employed extensively in the construction industry. Steel and metals have been used in both building's structural and cladding applications. Most of these metals are found on the earth combined with other substances.

The demand for the metal is expected to increase rapidly in the coming years as a result of technological advances, and economic and urbanization growth. For instance, the projected demand for iron has been estimated as three to four times higher in 2050 compared to 2010 (Muller, Lai, Beylot, Boitier, & Villeneuve, 2020). Similarly, the global steel demand is expected to have an average global growth of 3.3% per annum from 2012 to 2025 (PWC-Metals, 2015). Also, the extraction of metal ores will increase yearly by an average of 1.7% from 2015 to 2060 if the traditional consumption trend continued (Muller et al., 2020). According to Cullen et al. (2012), more than half of global steel production is employed by the construction industry in which half of it is used in building structures. Aluminium, on the other hand, is the second-most-used metal after iron. The aluminium production has grown an average of 2.5% per year for the last 25 years (Sverdrup, Ragnarsdottir, & Koca, 2015). The demand for aluminium is expected to increase by 2-3 timers by the year 2050 (Haraldsson & Johansson, 2018).

Most metals are extracted from the ores found in the Earth's crust. The production of metals (especially the processing of the ores) is an energy-intensive industrial sector that contributes to global emissions and, thus, escalating a range of environmental impacts related to climate change, biodiversity loss, and human health (Watari, Nansai, & Nakajima, 2021). Also, the global annual demand for iron and steel is estimated to be around 5-9% of global emissions (Cullen et al., 2012; Davis et al., 2018). According to D'Amico & Pomponi (2018), the steel industry accounts for about 25% of the total global CO_2 emissions. In 2016, energy-related emissions from the manufacturing of iron and steel represent 7.2% of the total energy used in industry (See **Figure 3-4**).

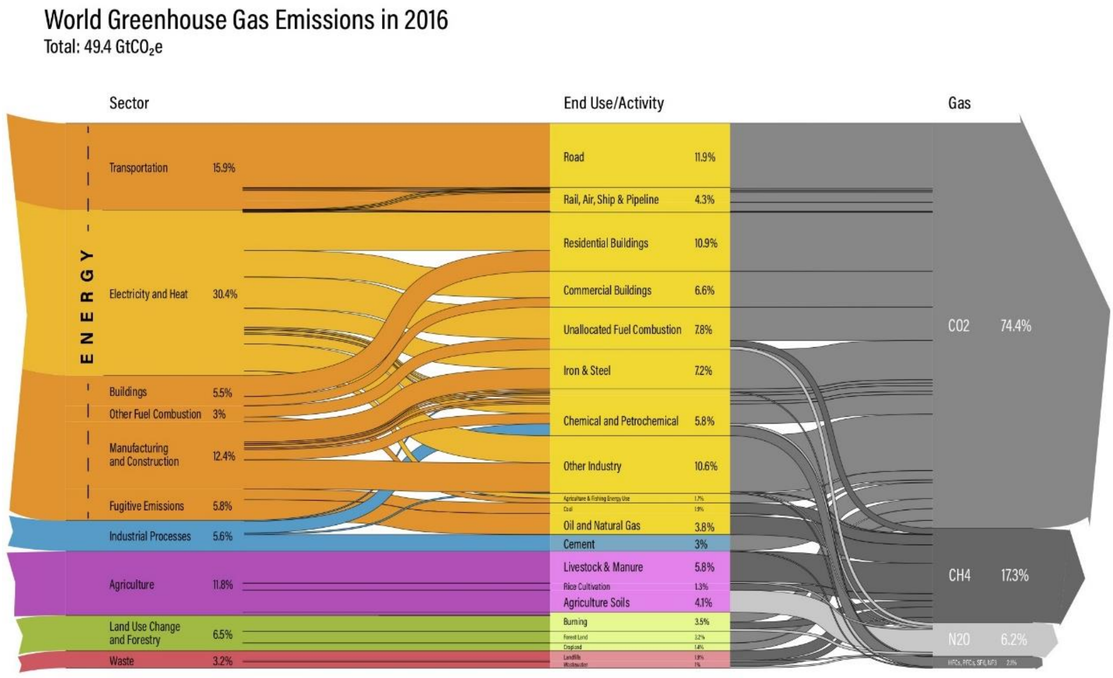


Figure 3-4: World Greenhouse Gas Emissions in 2016 by sectors

Source: World Resources Institute (2020)

Energy is consumed at all stages in the production of primary metals during mining, beneficiation and chemical extraction. The embodied energy of the common metals varies widely. For instance, the average data gave by ICE (2011) show the embodied energy of virgin steel and aluminium is 35.4 MJ/kg and 218 MJ/kg, respectively. It is worth noting that, although steel has a low embodied energy content, it is produced in the largest quantity. Thus, steel production contributes to the greatest quantity of greenhouse gases. Titanium, on the other hand, requires an exceptionally large amount of energy to process, almost 10 times that of steel. The embodied energy and embodied carbon of common metals are shown in **Table 3-3**.

To promote the development of sustainable metal products and reduce the carbon dioxide emissions of metal manufacturing, it is recommended to apply biomass, solar thermal technologies, and the electric arc furnace steelmaking technology in the metals production plants and also applying the carbon sequestration methods (Nidheesh & Kumar, 2019; Strezov, Evans, & Evans, 2013). Likewise, using recycled metals can significantly reduce the amount of energy (requires low temperatures) and carbon dioxide emissions compared to virgin metals (Echarri-Iribarren, Echarri-Iribarren, & Rizo-Maestre, 2019; Hodgkinson & Smith, 2018).

Construction materials	Embodied energy (MJ/kg)	Embodied carbon (kg CO_2/kg)
Aluminium	218	11.46
Recycled aluminium	29	1.69
Iron	25	1.91
Steel	35.4	2.71
Recycled steel	9.40	0.44
Stainless steel	56.7	6.15
Copper	57	3.65
Recycled copper	16.50	0.80
Titanium	361 to 745	19.20 to 39.90
Recycled titanium	258	13.70
Zink	72	3.90
Recycled zinc	9	0.49

Table 3-3: Embodied energy and embodied carbon of common metals

Adapted from (Hammond, Jones, Lowrie, & Tse, 2011)

In recycled metals, energy is only required for melting the metals and not for chemical transformation (most of the energy-intensive steps used in primary production will be excluded) (Gutowski, Sahni, Allwood, Ashby, & Worrell, 2013). For instance, recycled aluminium only uses 5% of the energy (2.8 kW/kg) required for the production of primary aluminium (13 kW/kg) (Tabereaux & Peterson, 2014). And for steel, it could be just 50 % of the primary energy intensity (Ashby, 2013). Generally, most of the metals can be infinitely recycled without losing their integrity.

On the other hand, many metals are used widely as wall cladding systems (metal panels) due to their ability to be recycled and their durability in many conditions. The metal wall panels are commonly used in commercial, residential and industrial buildings. These panels can be fabricated from a variety of materials including aluminium, copper, stainless steel, steel, titanium, and zinc. In this regard, aluminium is one of the most used metals in the construction industry and is a popular option for cladding (H. Radhi, 2010). Aluminium is strong, lightweight, durable, resistant to corrosion, and it can be recycled without losing its quality by comparison to other metals.

In terms of composition, two types of metal panels are available; single skin metal panels and metal composite materials (MCM) or insulated metal panels. The single skin panel is a single layer of prefinished or natural metal that has been formed into the desired profile. This panel type can be installed in less time, with less cost and can be easily recycled compared to other metal panel systems. Insulated metal panels or MCM, on the other hand, are composite panels made by filling an insulation heat material or other fire-retardant thermoplastic materials between two metal plates under specific heat and pressure. The core heat insulation material is typically composed of polyurethane or Rockwool materials (Yılmaz, Arslan, & Bideci, 2019). These types of panels are extensively used because of the insulation and energy-saving advances offered. However, the ability to be recycled at the end of their life depends on how they are mixed and integrated with other materials and the complexity of recovery.

3.1.4 Timber products

Since ancient times, wood/timber has been used as raw materials for construction and non-construction functions. It has been used worldwide in almost every country (A. Silva & Prieto, 2021). It has been widely applied in residential buildings (Mahapatra, Gustavsson, & Hemstrm, 2012). According to the estimates, wood-frame residential buildings account for approximately 45% of buildings in Japan, 90% of homes in North America, and up to 45% of dwellings in the northern European area (Mahapatra et al., 2012; Nunes, de Melo Moura, Güths, Atem, & Giglio, 2020). Timber is natural, renewable, recyclable, and biodegradable material with low embodied energy and low carbon impact (can store carbon[11] for decades). **Table 3-4** shows the embodied energy and embodied carbon of commonly utilized wooden products from cradle to gate Adapted from (Hammond et al., 2011) and other sources.

Wood Products		Embodied Energy (EE)- MJ/kg	Embodied Carbon (EC)- $kgCO_2/kg$
Solid wood	Sawn Hardwood	10.40	0. 128
	Sawn Softwood	7.40	0. 123
Engineered wood	Cross-Laminated Timber (CLT)**	12.34	1.08
	Glue Laminated Timber (GLT)*	11.08	0.75
	Laminated Veneer Lumber (LVL)*	9.68	0.48
Wood panels	Cork	4.00	0.19
	Woodwool (board)	20.00	0.98
	Medium Density Fiberboard (MDF)	11.00	0. 161
	Particleboard	14.50	0. 139
	Oriented Strand Board (OSB)*	17.12	1.05
	Hardboard (High Density Fibreboard)	16.00	0. 234
	Plywood	15.00	0. 221

Table 3-4: Embodied energy and embodied carbon for different wooden products

* source= (Puettmann & Wilson, 2005); ** source= (Kavanagh, 2016)

[11] One cubic metre of wood stores around one tonne of CO_2, making timber the only construction material that can impact positively on the environment.

The environmental impacts of timer construction are very small compared to steel and concrete. For instance, in a case study conducted in Melbourne-Australia, the global warming potential of 10 storeys apartments buildings constructed with timber was 22% lower than a reference building constructed with reinforced concrete (Durlinger, Crossin, & Wong, 2013). In another report, replacing 17% of brick, aluminium, steel and concrete with timber in construction can reduce around 20% of the greenhouse gas emissions (Jayalath et al., 2020).

According to Himes and Busby (2020), by applying the wood products in half of the new urban construction, approximately 9% of the emissions targets of 2030 might be achieved. Moreover, timber products can provide a lightweight construction compared with mass material (total timber building structural weight is around 20% of concrete), and they have a great prospect for reuse and recycling into other wood-based materials at the end of the building lifetime. Nowadays, wood from a sustainable source (ex. sustainably managed forests) is considered one of the most environmentally friendly existing construction materials.

Despite the numerous advantages of their use, timber products have some limitations that hinder their application in several construction types; for instance; low dimensional stability, hardness and wear resistance, and the ability to resist fire (S. Ahmed & Arocho, 2020). Nevertheless, modern engineered wood products are developed to enhance the timber properties by applying chemical, biological, mechanical, or physical agents to extend the durability of the products and to overcome the mentioned drawbacks of wood (Sandak, Brzezicki, & Sandak, 2020). Besides, the timber products are protecting against fire by the application of fire retarding agents (coatings) or by integrating fire protecting claddings on the fire exposed side of the elements (gypsum plasterboard and wood-based panels) (Kolaitis, Asimakopoulou, & Founti, 2014).

Nowadays, engineered wood products (EWPs) are widely used in modern construction practices. Engineered wood is a composite material consists of multiple wood boards formed by at least three basic processing steps, namely peeling or cutting, drying, and strength grading (Xiaofeng Sun, He, & Li, 2020). Traditionally, wood-framed buildings are mostly used for low-rise construction that is less than eight-story (Kordziel, Pei, Glass, Zelinka, & Tabares-Velasco, 2019). Nevertheless, several studies have been developed to investigate the possibility of using wood-based products in large-scale applications. For instance, Cross-Laminated Timber (CLT), Glued-Laminated Timber-Glulam, and laminated veneer lumber (LVL) are recently introduced in the construction market to expand the use of timber in large-scale construction projects and to promote the sustainability of cities (D'Amico, Pomponi, & Hart, 2021; Scouse, Kelley, Liang, & Bergman, 2020). In March 2019, the Mjosa Tower in Brumunddal- Norway, became the tallest wooden building in the world (18 floors and 85.4 m tall). Nowadays, the majority of timber products are prefabricated in the factory which allows faster construction and the implementation of the design for disassembly (DfD) approach.

Furthermore, some wood products can be integrated into the wooden assemblies to add bracing and shear strength or for acoustical and insulation purposes for example particleboard, plywood, oriented strand board, fibreboard, flake-board, wafer-board and hardboard (F. Asdrubali et al., 2017). **Figure 3-5** shows the schematic processing chain for the commonly used engineered wood products.

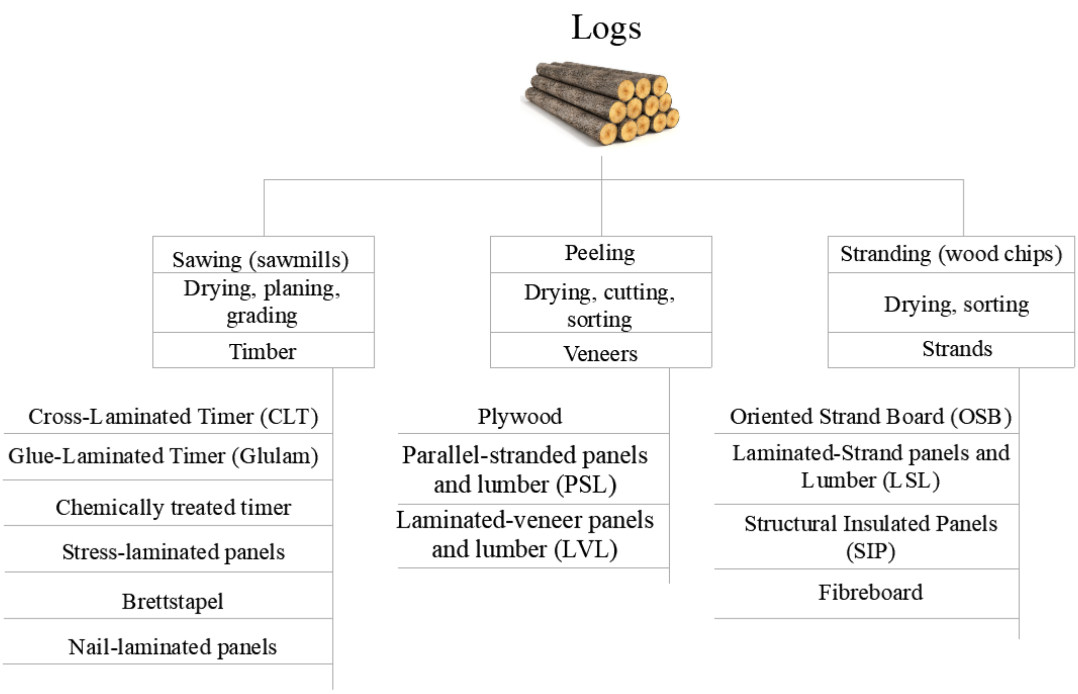


Figure 3-5: The schematic processing chain of engineered timber products
Adapted from (Ramage et al., 2017)

Timber products can be applied as exterior or interior cladding materials, and they could be installed vertically or horizontally as open wood faced with gaps or closed wood facades without gaps (Sandak et al., 2020). Furthermore, modern wood processing technology advances new composite materials that are suitable for use as external cladding in different climatic conditions. Several cladding materials from natural wood, thermally and chemically treated wood or wood-composite products have been used for façade cladding in different countries around the world. These might include thermo-treated timber products (thermo-wood) (Ivanović-Šekularac, Čikić-Tovarović, & Šekularac, 2016), wooden boards (Barreca & Tirella, 2017); wood composite materials (Friedrich, 2019, 2021; Friedrich & Luible, 2016b), fully prefabricated timber-based envelopes (Gasparri & Aitchison, 2019; Lehmann, 2013); insulated timer panels (Santos, Correia, Godinho, Dias, & Dias, 2020).

3.1.5 Earth products

Since early, the human being has utilized earth as a construction material due to its availability, versatility, mechanical, and insulating properties (Ávila, Puertas, & Gallego, 2021). Humans have been using earth construction techniques for at least as far back as 9000 years ago; numerous vernacular, as well as contemporary examples, can be found in many cultures and periods all around the world (for example Mesopotamia and Egypt, Romans, Africa and the Middle East, etc.) (Calatan, Hegyi, Dico, & Szilagyi, 2020; Hadji et al., 2020). Such kind of construction is mainly extended in hot-arid and temperate climate zones.

Up to date, about 30% of the world population live in earthen buildings (Olacia et al., 2020) and more than 2 billion people live in earthen houses across the world (Van Damme & Houben, 2018). Recently, earth construction received great emphasis due to the search for environmentally friendly building materials and methods (Sameh, 2014). Such kind of construction helps to save energy, provide thermal comfort, and reduce environmental pollution besides other social and economic advantages (Kasinikota & Tripura, 2021; Kulshreshtha et al., 2020; Minke, 2006).

Earth or soil is a naturally formed material consisting of particles of broken rock, mineral and organic elements. It is changed over time by chemical, biological and environmental processes. When earth used as a building material, it is generally a mixture of clay, silt (very fine sand), sand, and aggregates (gravel or stones). Several types of earth construction techniques are used, yet the most prominent are mud bricks or adobes (handmade unbaked bricks), soil blocks (compressed unbaked bricks), and rammed earth (compacted within a formwork). Nevertheless, the durability of earth construction and the effect of weathering on their properties has always been one of the most important concerns for designers and clients.

Rammed Earth (RE):

Rammed earth construction has increasingly attracted researchers towards creating a sustainable building solution. It has been commonly applied for constructing massive structures (L. Xie, Wang, Zhao, Gao, & Gallo, 2021). This construction technique is composed of compacting layers of soil between formworks (wooden or metal panels); each layer has a thickness of about 15 cm; the layers are compacted by the use of manual or pneumatic rammer (El-Nabouch, Bui, Plé, & Perrotin, 2017). The rammed earth materials are compacted close to their optimum moisture content (OMC) and maximum dry density (MDD). After compaction, each layer is 8–10 cm thick (Q. B. Bui & Morel, 2009). A new framework will be added above when the below one is filled. The process will be continued until reaching the preferred wall height. Generally, the rammed earth wall has a thickness ranges between 30 to 60 cm (Nowamooz & Chazallon, 2011). However, innovative manufacturing techniques are studied to create rammed earth wall, such as the use of prefabricated rammed earth wall blocks in a factory (Ruzicka, Havlik, Richter, & Stanek, 2015) and the 3D printing techniques (Kontovourkis & Tryfonos, 2020; Perrot, Rangeard, & Courteille, 2018; Ruzicka et al., 2015).

The rammed earth is a mixture of clay, silt, sand, gravel and stones. From ancient until today, rammed earth soil was stabilized by the addition of lime and cement to improve its strength and weathering resistance and to meet modern construction standards and requirements (Ciancio, Beckett, & Carraro, 2014; Jayasinghe & Kamaladasa, 2007). When additives are combined to enhance the mixture properties, the material is named stabilized rammed earth (SRE); and when the clay is used as the only additive (binder), it is referred to as unstabilized rammed earth (URE).

Although the addition of cement or lime can improve the durability and compression strength, they could result in a higher embodied energy and embodied carbon of the rammed earth due to the extraction and production process of these stabilizers (Serrano, Barreneche, Rincón, Boer, & Cabeza, 2013). For example, the embodied energy of 5% cement and 8% stabilized rammed earth is 0.68 MJ/kg and 0.83 MJ/kg, respectively. Recently, fly ash, natural or synthetic fibres and waste materials have been used as sustainable additives (stabilizers) to the rammed earth in order to reduce the environmental impacts in the building sectors (Arrigoni, Pelosato, Dotelli, Beckett, & Ciancio, 2017). See **Table 3-5**.

Additives/Binders used to enhance the sustainability of rammed earth	Reference (s)
Bottom Ash and Fly Ash/ Alkali-activated fly ash.	(Arrigoni et al., 2017; Cristelo, Glendinning, Miranda, Oliveira, & Silva, 2012; Da Rocha, Consoli, & Dalla Rosa Johann, 2014; Kosarimovahhed & Toufigh, 2020; Pflughoeft-Hassett, Debra, Dockter, Bruce A, Hassett, 2000; Raj S., Sharma, & Anand, 2018; Siddiqua & Barreto, 2018; R. A. Silva et al., 2013)
Rice Husk Ash.	(Milani & Labaki, 2012)
Straw, pneumatic fibres, and alabaster.	(Serrano et al., 2013)
Animal by-product (blood as a stabilizer).	(Kraus, Hirmas, & Roberts, 2015)
Ground-Granulated Blast-Furnace Slag and Silica Fumes.	(S.Jayakumar, J.Hemachander, & Hameedh, 2016)
Plant aggregates and fibres.	(Laborel-Préneron, Aubert, Magniont, Tribout, & Bertron, 2016)
Stabilised rammed earth mixtures incorporating recycled concrete aggregate.	(Arrigoni et al., 2018)
Guar gum, natural pozzolan and micro silica and some industrial stabilizers such as fibreglass, cement, and phase change material (PCM).	(Toufigh & Kianfar, 2019)

Table 3-5: The most commonly used alternative stabilizers in the rammed earth

Earth bricks (adobe) and compressed earth blocks (CEB)

Adobe or Mud Brick is made from clay, silt, sand and water, with some kind of fibrous or organic material (sticks, straw, dung), which is formed into bricks using moulds and then placed in the sun to dry. Adobe brick is typically manufactured and installed without the need for skilful labours or costly tools and is typically connected to low cost and fast construction (Dormohamadi & Rahimnia, 2020).

In the past, adobe was utilized in almost all types of construction and its use is declined in the middle of the 20th century with the development of the cement industry (Silveira et al., 2012). It has been estimated that 50 % of the developing countries live in houses made of unfired earth-based materials (Fratini, Pecchioni, Rovero, & Tonietti, 2011). However, the low strength and durability properties are the main threats that limited the use of adobe in modern construction practices (Li Piani et al., 2020). The compressive strength of the adobe is stated in the literature varying from 0.5 MPa to about 7 MPa, while the reported flexural strength was varied in a range from 0.5 MPa to about 1.5 MPa (Dormohamadi & Rahimnia, 2020). The clay mineralogy and the nature of the particle size distribution are the most important factors affecting the durability and speed of deterioration of adobe bricks.

The compressed earth blocks are a modern form of adobe brick; it is a combination of sand, silt and clay providing optimum strength when compressed, then left to dry. The compaction process offers high density to the CEB and significantly decreases its porosity, and increases its compressive strength and resistance to water damage. Nevertheless, the material is considered a sustainable alternative to the burnt clay bricks (Preethi & Venkatarama Reddy, 2020). In comparison to the fired clay brick, the most environmental advantages related to the use of CEB are few natural resources use, low embodied energy, and low CO_2 emission (Islam, Elahi, Shahriar, & Mumtaz, 2020).

According to Fernandes et al. (2019), a 1 m^2 wall of compressed earth block and rammed earth represent half of the carbon emissions and embodied energy than ceramic brick or concrete block. The production of compressed earth blocks (CEB) is similar to the rammed earth construction which produces material that is heavier and more durable than adobe bricks (Pacheco-Torgal & Jalali, 2012). Generally, the embodied energy of adobe, rammed earth, and compressed earth block is very similar; a typical figure of 0.45 MJ/kg is frequently used (Cabeza, Boquera, Chàfer, & Vérez, 2020).

The addition of several stabilizers such as cement, coarse aggregate, bitumen, lime, gypsum, glass waste, ground granulated blast furnace slag, fly ash, sugarcane bagasse ash, crushed brick waste, fibres, or a combination of these materials has proven successful in increasing the mechanical properties and durability of CEB (Bekhiti, Ghrieb, & Zaitri, 2021; Cottrell, Ali, Tatari, & Martinson, 2021; Elavarasan, Priya, Raja Gurusamy, Mohamed Riyas Naveeth, & Natesh, 2020; Kasinikota & Tripura, 2021; Lima, Varum, Sales, & Neto, 2012; Oti, Kinuthia, & Bai, 2009; Rivera et al., 2021). In the past years, natural fibres have been used as the most common stabilizer for adobe bricks in several research studies. The obtained results proved their role in the mechanical and thermal properties of adobe bricks (Khoudja et al., 2021).

In general, cement and lime are the most commonly used materials to stabilize the CEB. Yet, the high embodied energy and carbon footprints associated with the utilization of these materials are considered as the key drawback (Gupta, Chai, Lu, & Chaudhary, 2020). Therefore, incorporating proper additives (stabilizers) as a replacement for the industrial stabilizers is considered a sustainable approach to reduce the environmental impacts of these materials. In this regard, industrial wastes or by-products and agricultural wastes are considered an ideal alternative for this particular application.

3.1.6 Insulation products

Using efficient insulation materials is very important to reduce energy consumption as well as the impact of urban noise. There are several types of insulation materials varying from traditional synthetic or inorganic (e.g., glass, rock, slag wool, and ceramic products) to natural ones or organic (e.g., cellulose, cotton, wood, pulp, cane, polystyrene, polyethylene, polyurethane, and other polymers) (Abu-Jdayil, Mourad, Hittini, Hassan, & Hameedi, 2019). Most of the insulation materials are produced from petrochemicals or from highly processes natural materials. However, these materials have diverse environmental impacts due to the consumption of non-renewable materials and fossil energy consumption during the production stage, and the problems of their reusing and recycling at the end of their lifetime (Francesco Asdrubali, D'Alessandro, & Schiavoni, 2015).

As regards the environmental impacts, the blowing agents which are responsible for the thermal properties of the insulation materials, play an important role in determining their sustainability. Hydrofluorocarbons and other blowing agents are used in foam insulation such as extruded polystyrene and polyurethane foams (Shrestha, Biswas, & Desjarlais, 2014). The chlorofluorocarbons (CFCs) were found in the late 1950s and they widely used in the foam's production due to their excellent properties. However, in the early 1980s, chlorofluorocarbons (CFCs) was proven as an ozone-depleting substance. Subsequently, they were substituted by hydrochlorofluorocarbons (HCFCs). Although HCFCs present a considerably lower ozone depletion potential (ODP) than CFCs, their global warming potential (GWP) is higher. As a result, hydrofluorocarbons (HFCs) were developed with zero ozone depletion potential but still high global warming potential. Recently several alternative blowing agents have been found, for instance, natural inert gas (carbon dioxide, nitrogen), hydrocarbons (HC) and hydrofluoroolefins (HFOs). Currently, HFOs are believed to be the most sustainable alternative because of their low GWP and zero ODP (Coste, Negrell, & Caillol, 2020).

The blanket insulation in the forms of batts or rolls and foam boards have been used as the main conventional insulation materials a long time ago. The blanket insulation types include mineral wool, fibreglass, plastic fibres, and natural fibres, while typical foam board insulation materials include polystyrene (expanded polystyrene (EPS) and extruded polystyrene (XPS)) and polyurethane (Streimikiene, Skulskis, Balezentis, & Agnusdei, 2020). The second polymers type are commonly acknowledged to be good insulating material because of their stable chemical and physical properties. However, they are vastly combustible and could generate great amounts of poisonous gases (Stec & Hull, 2011). **Table 3-6** shows the thermal properties, embodied energy and embodied carbon of the conventional insulation materials.

Conventional insulation type	Manufacturing process	Density kg/m^3	Thermal conductivity W/m.K	Specific heat capacity kJ/(kg·K)	Embodied energy MJ/kg	Embodied carbon $kgCO_2/kg$
Mineral wool (rockwool)	It is produced by melting rock materials (slags and ceramics) at 1600°C and blowing air or steam through the curing oven to generate the fibres.	50 ± 1	0.042 ± 0.0002	960	16.6	1.20
Fibreglass (glass wool)	It is manufactured by mixing sand and recycled glass and melting them at a temperature of about 1450°C to produce glass. Then the glass is changed into fibres by forcing it through a mesh and cooling it by contact with air. A binder agent is added in advance to secure the bonding and mechanical strength.	30 ± 1	0.042 ± 0.0006	840	28	1.35
Expanded Polystyrene (EPS) or Extruded Polystyrene (XPS)	The PS is made by polymerizing styrene monomers in polystyrene before moulding it (EPS) or extruding it (XPS) into rigid foam panels.	28 ± 1	0.032 ± 0.0003	1280	88.60	2.55
Polyurethane (PU)	PU is manufactured by combining a stream of isocyanate and a stream of a polyol with any other additives.	28 ± 1	0.024 ± 0.0005	1470	101.50	3.48

Table 3-6: Thermal properties, embodied energy and carbon of the conventional insulation materials

*Note: Thermal properties values adapted from (Al-Ajlan, 2006), Embodied energy and embodied carbon figures adapted from (Hammond et al., 2011).

Recently, new insulation materials have been acknowledged through several studies to participate in creating insulating materials that have great properties and less environmental impact. Several studies have been focused on the utilization of natural fibres and wastes (industrial and agricultural) in the development of eco-friendly thermal insulation materials. Indeed, the use of natural fibres has several advantages over synthetic fibres, as the former is considered environmentally friendly and renewable materials (Zach, Hroudová, Brožovský, Krejza, & Gailius, 2013). **Table 3-7** shows the most recent approaches to create alternative insulation materials.

Alternative insulation type	Optimization Techniques/Methods/Materials	Reference (s)
Biodegradable fibres for use as building thermal insulation.	Coconut fibre and sugarcane fibre.	(Manohar, Ramlakhan, Kochhar, & Haldar, 2006)
Extruded and pressed thermal insulators made with rice husk ashes	The thermal insulators were produced from several different formulations containing rice husk ashes, plasticizer additives and binders, wood sawdust, flux, and water.	(M. R. F. Gonçalves & Bergmann, 2007)
Fly ash-scrap tire fibre composite insulation.	Adding fly ash-scrap tire fibre composite to traditional fibreglass insulation.	(van de Lindt, Carraro, Heyliger, & Choi, 2008)
New insulating particleboards from solid wastes and corn peel.	A mixture of solid wastes from tissue paper manufacturing and corn peel have been developed. Besides, recycled polystyrene packaging foam used as a laminating agent to improve the quality of the boards.	(Lertsutthiwong, Khunthon, Siralertmukul, Noomun, & Chandrkrachang, 2008)
An environment-friendly thermal insulation material—binderless cotton stalk fiberboard.	Cotton stalk fibres without resins and other chemical additives.	(Xiao yan Zhou, Zheng, Li, & Lu, 2010)
Sustainable acoustic and thermal insulation materials from elastomeric waste residues.	Mixing the foaming binder with the waste residue particulates then forming the compound in a mould with or without consolidation to control expansion.	(Benkreira, Khan, & Horoshenkov, 2011)
Natural thermal-insulation materials composed of renewable resources.	Different insulation plates of jute, flax and hemp are manufactured.	(Korjenic, Petránek, Zach, & Hroudová, 2011)
Ecological thermal insulation material from agricultural waste.	Using corn's cob based material as a panel.	(Pinto et al., 2011)
Thermal insulation from natural material.	Date palm wood.	(Agoudjil, Benchabane, Boudenne, Ibos, & Fois, 2011)
Low-density thermal insulation boards.	Coconut husk and bagasse.	(Panyakaew & Fotios, 2011)
Sheep wool.	Alternative uses of wool as a construction material beyond its traditional uses in the textile industry.	(Korjenic, Klaric, Hadžic, & Korjenic, 2015; Zach, Korjenic, Petránek, Hroudová, & Bednar, 2012)
Building thermal insulation from agricultural By-Products.	Oil palm, coconut and sugarcane fibre.	(Manohar, 2012)

Alternative insulation type	Optimization Techniques/Methods/Materials	Reference (s)
Light-weight chipboards produced from cotton waste, fly ash and barite.	Fly ash, epoxy resin, cotton waste and barite were mixed at different rates and then applied between chipboards.	(Binici, Gemci, Kucukonder, & Solak, 2012)
Thermal insulation board from Narrow-leaved Cattail Fibers.	Hot pressing was employed to produce single-layered plain thermal insulation boards.	(Luamkanchanaphan, Chotikaprakhan, & Jarusombati, 2012)
Textile waste as an alternative thermal insulation building material.	Woven fabric waste and woven fabric sub waste.	(Briga-Sá et al., 2013)
Industrial solid wastes as alternative building thermal insulation materials.	Material wastes (two leather wastes and two carpentry wastes) deposited between plasterboards and cement boards.	(Lakrafli, Tahiri, Albizane, Bouhria, & El Otmani, 2013)
Silkworm cocoon as natural material and structure for thermal insulation	The thermal insulation of four types of domestic and wild Silkworm cocoon walls was studied.	(J. Zhang, Rajkhowa, Li, Liu, & Wang, 2013)
Insulation panels based on textile recycled fibers.	Textile waste material.	(Valverde, Castilla, Nuñez, Rodriguez-Senín, & De La Mano Ferreira, 2013)
Environmentally friendly composites derived from the sugar palm tree.	Sugar palm fibre (SPF) reinforced plasticized sugar palm starch (SPF/SPS) bio-composites.	(Sahari, Sapuan, Zainudin, & Maleque, 2013)
An environmentally friendly thermal insulation material from sunflower stalk, textile waste and stubble fibres.	The fibre insulation material was produced with sunflower stalks, cotton waste, and textile waste fibre and epoxy as binder materials.	(Binici et al., 2014)
Porous thermal insulation material using coal fly ash as the main raw material.	Coal fly ash as raw material, waste glass as additional material, clay to enhance the strength, Sodium dodecyl was employed as foaming agent and a certain amount of sodium polyacrylate was selected to stabilize the foams.	(R. Zhang et al., 2014)
Building insulation products made of natural sources or recycled products.	Natural thermal insulation materials include reeds, bagasse, cattail, corn cob, cotton, date palm, durian, oil palm fibre, pineapple leaves, rice, sansevieria fibre, sunflower, and straw bale. Recycled thermal insulation materials include recycled glass foam and fibers, recycled plastics, recycled cotton and denim, recycled textile fibers, recycle fly ash residue.	(Francesco Asdrubali et al., 2015)
Thermal and sound insulation materials from waste wool and recycled polyester fibers.	Mixing waste wool fibres (coring wool and Dorper wool) and recycled polyester fibres.	(Patnaik, Mvubu, Muniyasamy, Botha, & Anandjiwala, 2015)
Corkwood and its composites for building insulation.	Sandwich assemblies were prepared by adding cork between two wooden plates.	(Limam, Zerizer, Quenard, Sallee, & Chenak, 2016)
Insulation materials made from natural fibres of agricultural origin.	Straw, hemp and cellulosic fibres.	(Reif, Zach, & Hroudová, 2016)
Recycled textile materials for building insulation.	Two samples of textile waste were produced by shredding and mixing	(Hadded, Benltoufa, Fayala, & Jemni, 2016)
Cellulose fibre insulation	Ground paper fibres treated with inorganic additives.	(Lopez Hurtado, Rouilly, Vandenbossche, & Raynaud, 2016)

Alternative insulation type	Optimization Techniques/Methods/Materials	Reference (s)
Thermal insulation panels made of black locust tree bark.	Various bark panels were made from black locust shredded bark.	(Pásztory, Ronyecz Mohácsiné, & Börcsök, 2017)
Bio-insulation building materials based on bamboo fibers and bio-glues	Fiberboards were manufactured from bamboo fibres and bio-glues (a mixture between bone and sodium lignosulfonate glues).	(D. M. Nguyen, Grillet, Diep, Ha Thuc, & Woloszyn, 2017)
An environment-friendly new insulation material involving waste newsprint papers reinforced by cane stalks.	Waste newsprint papers, cane stalks, vermiculite, perlite, zinc borax and plaster (as the binder).	(Aksogan, Resatoglu, & Binici, 2018)
Wood waste as a thermal insulation material.	Wood waste material was used without the addition of binders and applied to timber frame wall construction.	(Cetiner & Shea, 2018)
Eco-friendly bio-insulation material based on wheat straw for buildings.	Wheat straws as raw material and geopolymers were used as mineral binders.	(L. Liu et al., 2019)
Bio-based insulation materials from vermiculite, sunflower stalk and wheat stalk.	Mixing sunflower stalk, wheat stalk, and vermiculite with gypsum as a binder.	(Binici et al., 2020)
Alkali-extracted tree bark for efficient bio-based thermal insulation.	Reducing the density of the bark by means of a mild alkaline extraction.	(Busquets-Ferrer, Czabany, Vay, Gindl-Altmutter, & Hansmann, 2021)
An environmentally-friendly sound insulation material from post-industrial textile waste and natural rubber.	Using cotton/polyester mixed wastes and natural rubber (as a bonding agent).	(Dissanayake, Weerasinghe, Thebuwanage, & Bandara, 2021)

Table 3-7: Most common studies in the area of building insulation materials and technologies

3.1.7 Glass and Glazing

Glass is a brittle and low heat conductive material, therefore it is regarded as one of the weakest parts of buildings (Q. Xie, Wang, Guo, & Ma, 2021). The main compound of glass is silica (SiO_2), which is the main compound of sand. It is combined with soda ash (Na_2O) and limestone (CaO) and melted together in a furnace at high temperatures of 1600–1800°C. Other Separated additives can be used to produce coloured glass.

Commercial glass is generally known as Soda Lime Glass or Silica-Lime Glass. It is the most widely used silica-glass type in the construction industry. Typically, it comprises approximately 69– 74% silica, 5–14% lime, 10–16% soda and other small components such as magnesia (MgO) and alumina (Al_2O_3) (Haldimann, Luible, & Overend, 2008; Karazi, Ahad, & Benyounis, 2017). The soda-lime glass in its flat sheet form is sometimes advanced to manufacture tempered glass or laminated glass (safety glazing materials)

(Achintha, 2016). Tempered (toughened) glass is treated by controlled thermal or chemical treatments to increase its strength. The laminated glass has great post-breakage performances and other special properties such as fire resistance and noise control.

In 2018, the world total production of glass was about 130 million tons (Jani & Hogland, 2014). This number is expected to rise due to the increase in industrialization and urbanization, as a result, the waste glass will increase. The manufacturing process of glass is linked to the utilization of a huge amount of natural resources, energy consumption and the production of greenhouse gases (GHG), thus, it has negative impacts on the natural environment. According to Jani and Hogland (2014), it was estimated that the production of each kilogram of sheet glass consumed around 1.73 kg of raw materials and 0.15 m^3 of water. Also, soda-lime glass (primary glass) has an embodied energy of 15 MJ/kg and embodied carbon of 0.86 $kgCO_2/kg$ (Hammond et al., 2011). This high embodied energy figure is associated with the requirements of melting the silica for ten hours at 1500-1600°C temperature (P. Guo, Meng, Nassif, Gou, & Bao, 2020; Schmitz, Kamiński, Maria Scalet, & Soria, 2011). **Figure 3-6** shows a large variety of ecological indicators of different glazing products.

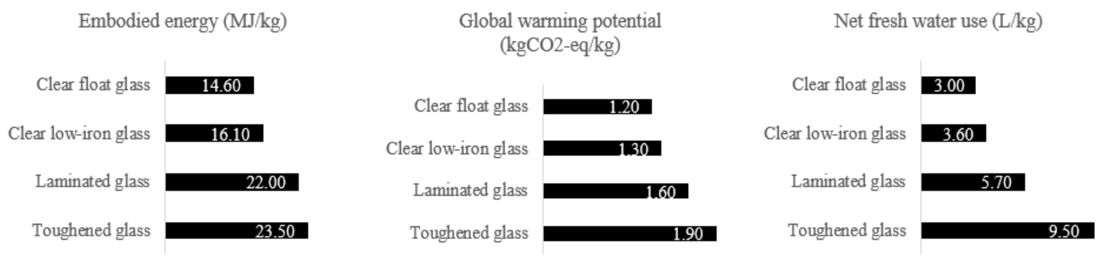


Figure 3-6: ecological indicators of various glazing products from Cradle to gate.

Adapted from (Souviron, van Moeseke, & Khan, 2019)

Moreover, the number of glass panes (single, double, and triple-glazed systems), the gas filling the cavity in multi-panes glass (air, argon, xenon or krypton), and the glass coatings (low emissivity or solar control) all have an influence on the embodied impacts (Saadatian, Freire, & Simões, 2021). For instance, the manufacture of one square meter of Low-E double glazing can generate around 25kg of CO_2 emission (Nippon Sheet Glass Group, 2010). Likewise, the frame of the glazing units play an important role in determining the energy efficiency of the buildings, and the embodied energy and embodied carbon for the whole system (Souviron et al., 2019).

Although climate locale is a very critical aspect to determine the suitability of glazing in buildings, highly glazed buildings have become an international design image in modern architecture which have been built in any type of climate (Lau, Salleh, Lim, & Sulaiman, 2016). This has put the squeeze on the global environmental concerns specifically energy consumption and global warming worsening (Chow, Li, & Lin, 2010).

According to Arnesano et al. (2021), the facades' glazing is one of the least energy-efficient building's components. They are responsible for approximately 15–22% of a building's energy loss. However, the essential need to reduce energy consumption and maximize the use of natural daylight (open view) to enhance occupant's well-being in buildings has promoted the use of green and sustainable glazing systems. In this respect, several strategies have been implemented to guarantee adequate visual transmittance, reduced glare and low thermal losses (U-value) through the glazing façade (Syrrakou, Papaefthimiou, & Yianoulis, 2005), for instance, replacing single glazed facades with double glazed facades or a single clear glass with Low-E (low-emissivity) double glazing and the use of self-cleaning glass and thermochromic glazing technology.

Recently, thermochromic glazing materials or switchable glazing have been acknowledged as a promising sustainable technology that displays energy saving by regulating the incoming solar radiation concerning external and internal thermal variation (Arnesano et al., 2021; Syrrakou et al., 2005), thus it can be applied despite the climatic conditions.

Glass is difficult to biodegrade and the process could take several hundred years to fulfil (J. Yu, Tian, Xu, & Wang, 2015). On the other hand, glass, like metal, is a 100% recyclable material and can be remelted an unlimited number of times. In this respect, recycled glass known as a cullet can be used to produce new glass. In 2016, the waste glass (cullet) accounted for 5% of the total waste produced worldwide (D. Kazmi, Serati, Williams, Qasim, & Cheng, 2021). However, utilizing a cullet has several environmental and economic advantages; it conserves the natural resources by reducing quarrying, and saves energy and reduces emissions since recycled glass (cullet) melts more easily and leads to decreasing costs (Achintha, 2016).

Currently, the use of a cullet as a post-consumer glass (at the end of the building lifetime) is considered very low. This is mostly due to the complexity of removing the coatings and other contaminated materials mixed with waste glass. Also, the low energy savings from recycled glass is another major barrier. For instance, 5% of energy can be saved by using recycled glass while 95% of energy savings could be achieved by utilizing recycled aluminium. Even though recycling waste glass is not significantly attractive, it can be reused in several ways (ex. aggregate in concrete or additives to produce other construction materials). Hence reusing waste glass is greener than recycling it.

To sum up, the energy performance balance between the manufacturing of high-performance glazing products and the embodied impacts (energy, carbon, and water) expended in the manufacturing process must be considered in the selection of sustainable glazing alternatives.

3.1.8 Composite materials

Composite materials are engineered or naturally occurring materials constituted from two or more elements with notably distinct physical or chemical properties (Cabeza et al., 2020). Typically, one of these two materials is the binding material and the other is the reinforcing material (the main contributor to the strength of the composites) (Fayomi, Okwilagwe, Agboola, Oyedepo, & Popoola, 2020). For instance, in a straw mud-brick, the straws are the reinforcing fibres while the clay is the binder (matrix). However, the combination between the matrix and reinforcement during manufacturing have diverse impacts on the final product (Rodonò, Sapienza, Recca, & Carbone, 2019). The main purpose of engineered composites is to obtain more stable products with the combined properties for their constituents.

Demand for composites is expected to increase and global demand is estimated to double (Rybicka, Tiwari, & Leeke, 2016). Composite materials have notable properties which have made them preferred to conventional materials such as high strength, durability, and cost (Brigante, 2014). Their use in the construction industry is increasing rapidly; they have been used extensively in the exterior and interior applications of contemporary architecture. Currently, the advanced composite materials mainly signify the evolution of the science and technology of materials and they have presented themselves with much greater performance and sustainability (Fayomi et al., 2020). Furthermore, the application of composite materials as an alternative to traditional building materials (concrete, steel, or aluminium) has made modern building construction substantially more adaptable and achievable (can be moulded into complex shapes) (Owoyale Adeola & Tauheed Alfa, 2018). Composite materials are generally categorized based on the physical or chemical characteristics of the matrix, such as metal matrix or polymer matrix.

Nowadays, different types of engineered composite materials are developed to be used in building facades (composite cladding panels) include wood-plastic composites (WPC), Fibre-reinforced polymer (FRP) composites, Metal composite materials (MCM), and other advanced composite materials (See **Table 3-8**).

Composite materials	**Methods/Strategies/Materials**	**Sustainability indicator/s**	**Reference(s)**
wood-plastic composites (WPC)	Wood fibres embedded in a petrochemical plastics matrix.	The production of WPC and its recycling is comparatively less energy-consuming compared to conventional building materials such as metal or cementitious products.	(Friedrich & Luible, 2016a; Keskisaari & Kärki, 2018)
Wood-cement composites (WCP)	Wood wool which is usually spruce (softwood) or poplar (hardwood), mixed with a binder which is commonly ordinary Portland cement (OPC) or white cement (WC).	Low energy consumption, lightweight, low-cost and easy to process and fabricate.	(Berger, Gauvin, & Brouwers, 2020; Noh, Ahmad, Ibrahim, & Walker, 2016)
Fibre-reinforced polymer (FRP) composites	FRP composites are composed of fibre reinforcements (carbon, glass, aramid and basalt fibres) and a resin matrix (polyester, epoxy and vinyl ester) that bonds the fibres.	Prefabricated modular construction applications (eliminate waste on construction sites), lightweight, low embodied energy, and high-performance materials.	(T. Q. Liu, Liu, & Feng, 2020; Q. Nguyen, Ngo, Mendis, & Tran, 2013; Q. T. Nguyen et al., 2016)
Fibre-reinforced concrete/cement composites (FRC)	Natural or glass fibres are embedded in the cementitious matrix.	Durable, lightweight, weather-resistant, and high recycled content products,	(Henriksen, Lo, & Knaack, 2015; Joshi, Drzal, Mohanty, & Arora, 2004; C. Zhou, Shi, Chen, Cai, & Smith, 2018)
Metal composite materials (MCM)	Two sheets of corrosion-resistant metal bonded to an extruded thermoplastic (PE) /Insulating foam/ fire-retardant thermoplastic (FR).	Lightweight, durable, recyclable and high recycled content products.	(Yılmaz et al., 2019)

Table 3-8**:** The recent commonly used composite materials for building facades

The Utilization of natural materials for the production of composites has lower environmental impacts compared to artificial or non-renewable materials. Additionally, the use of industrial, agricultural, construction and demolition waste as a replacement of virgin materials for the production of composite materials is considered a sustainable move towards resource efficiency, energy efficiency, and carbon footprint reduction. For instance, the climate change impacts of manufacturing 1 kg of wood-plastic composites (WPC) from waste varied between 0.40–0.80 kg CO_2-eq which is more environmentally favourable than the production of WPC from virgin materials (2.2 kg CO2-eq per kg of virgin plastic used) (Liikanen et al., 2019; Sommerhuber, Wenker, Rüter, & Krause, 2017; Sormunen, Deviatkin, Horttanainen, & Kärki, 2021).

On the other hand, the combined nature of the composite materials makes them infeasible for recycling. Typically, constituted materials need to be separated before using in the recycling plants. However, this is not always practicable or economically viable (Utekar, Suriya, More, & Rao, 2021). Besides, contamination is a major obstacle to composite recycling (Ignatyev, Thielemans, & Vander, 2014). Presently, the most common strategy of composite materials waste is dominated by landfilling (Conroy, Halliwell, & Reynolds, 2006; Rybicka et al., 2016). Therefore, designing composite materials and components for easier deconstruction, reuse and recycling at the end of composites life will play an essential role in reducing the construction and demolition waste and moving towards sustainability (Utekar et al., 2021). **Figure 3-7** shows the high cost and difficulty to recycle composites compared to other materials.

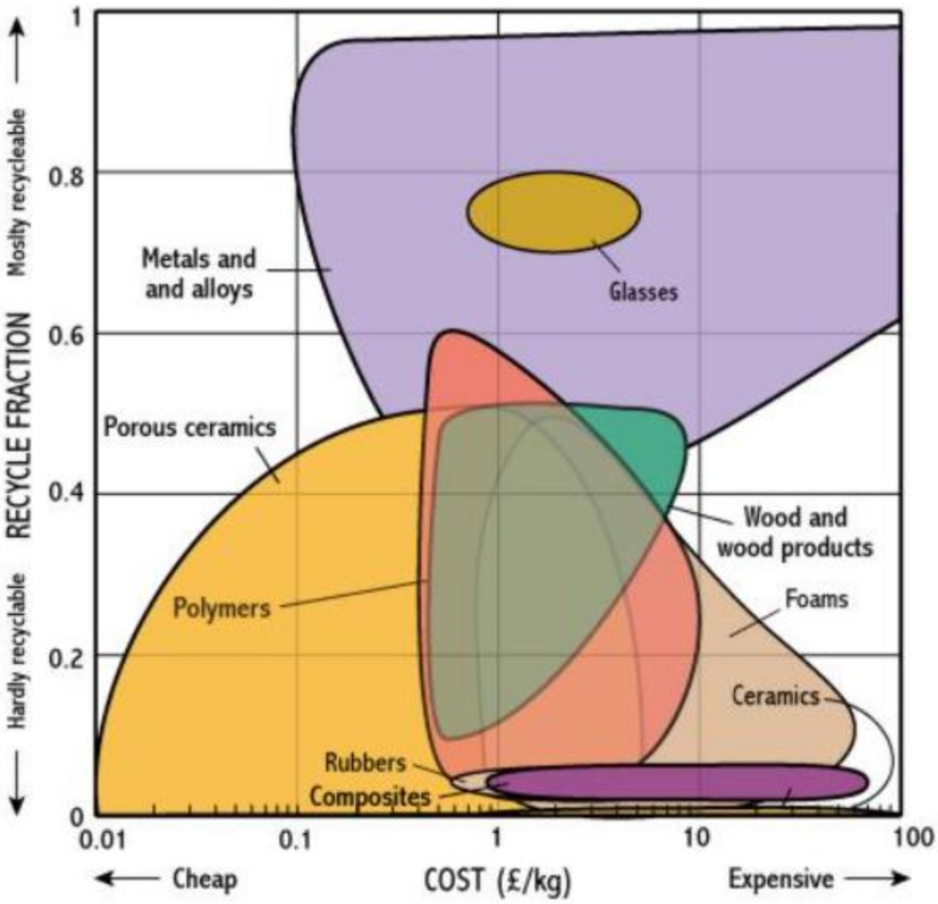


Figure 3-7: The recycle fraction-cost of composites in comparison to other materials
Source: (University of Cambridge-Department of Engineering, 2002)

3.1.9 Gypsum products

Gypsum is an ancient building material widely used for many applications in constructions that dates back 4000 years ago (Boccarusso et al., 2020). It is commonly known as calcium sulfate, which exists in hydrous and non-hydrous compounds: dihydrate ($CaSO_4 \cdot 2H_2O$), hemihydrate ($CaSO_4 \cdot 0.5H_2O$) and anhydrite ($CaSO_4$). Dehydrate is a sedimentary evaporate mineral that contains around 23% of calcium (Ca) and 18.6% of sulfur, and typically called gypsum. While gypsum and anhydrite are naturally occurring minerals, the hemihydrate can be shaped when dehydrate is heated at a temperature between 125°C and 180 °C (Amine Laadila, LeBihan, Caron, & Vaneeckhaute, 2021; Weimann, Adam, Buchert, & Sutter, 2021).

Gypsum products are lightweight and have great thermal, fire and sound resistance but low mechanical properties and water resistance (Lushnikova & Dvorkin, 2016). Gypsum can be applied as an alternative to lime and cement in interior plastering work and it can be used as blocks, boards and panels in partitions and internal walls in place of ceramic elements, cellular concrete blocks and other related products. The drywall (also called gypsum plasterboard or veneer plaster) is the most common gypsum plaster panel that is glued between two sheets of cardboard. They comprise the highest amount of used gypsum in buildings.

Globally, around 150 million tons of gypsum are manufactured yearly (Weimann et al., 2021), while around 15 million tons of gypsum residues are produced from construction, renovation and demolition waste activities (Amine Laadila et al., 2021). Although there is no global natural gypsum scarcity, mining can cause several impacts related to land occupation, energy use, and biodiversity loss (Jiménez Rivero, Sathre, & García Navarro, 2016). Gypsum-based products are known as being environmentally friendly materials. The environmental impacts of gypsum manufacturing are minor comparing to other building materials. Gypsum binders are energy-saving materials because calcination processes happen at considerably lower temperatures. In this regard, the embodied energy of gypsum plaster is around 1.8 MJ/kg, and its carbon footprint is 0.12 kg CO_2 per 1 kg. Additionally, gypsum plasterboard has an embodied energy of 6.75 MJ/kg and 0.38 kg CO_2/kg (Hammond et al., 2011).

On the other hand, direct reuse of gypsum products after demolition is uncommon (Lushnikova & Dvorkin, 2016). The gypsum waste constituted about 0.2%–0.4% by weight of the total construction and demolition waste (Gálvez-Martos, Styles, Schoenberger, & Zeschmar-Lahl, 2018). The greater part of this waste is from plasterboard, followed by gypsum blocks and plaster ceilings (Jiménez-Rivero & García-Navarro, 2020). Also, disposal of gypsum products has become a serious concern because they normally contain various contaminated substances and heavy metals which could cause several negative environmental and health impacts. However, several types of treatment and methods have been used for gypsum products that are polluted with heavy metals and organic contaminants to enable their recyclability and to reduce the hazardous substances of gypsum waste (hydrogen sulphide[12] (H_2S)) in landfills (Amine Laadila et al., 2021). Currently, the processing of gypsum waste into high quality recycled gypsum is achievable (Jiménez Rivero et al., 2016). In general, the recycling of gypsum waste is involving two steps; the collecting and separation of the waste, and the calcination.

Generally, gypsum waste has a comparable chemical constitution as a natural one. Hence, it is possible to be reused for the production of new gypsum products, and also it could be used as a substitute for natural gypsum in other construction applications such as retarders in Portland cement (Chandara, Azizli, Ahmad, & Sakai, 2009), cement replacement in concrete (Hansen & Sadeghian, 2020), and to improve the strength of soft clay soil for embankment construction projects (A. Ahmed, Ugai, & Kamei, 2011). Furthermore, to reduce the consumption of virgin materials and related impacts, the synthetic gypsum (obtained from different industrial processes) can be used as a partial or total substitute of natural gypsum in the production of construction materials (Pedreño-Rojas, Fořt, Černý, & Rubio-de-Hita, 2020). Also, various by-products have been used to enhance the properties of gypsum products for example slag, fly ash, silicate clinker, rubber particles, and fibres. However, their inclusive application is remaining low (Jia, Wang, & Feng, 2021).

To put it briefly, products manufactured from synthetic gypsum or recycled gypsum (recycled content) could contribute more to the sustainability of gypsum products. Currently, several gypsum-based composites have been used extensively in interior linings of walls (as load-bearing and non-loadbearing wall panels) due to their many economic and environmental benefits, such as hollow and solid gypsum concrete blocks (Júnior, Pinheiro, Silva, Pires, & Alencar, 2021), glass fibre-reinforced gypsum (GFRG) (Cherian, Palaniappan, Menon, & Anumolu, 2020), foam gypsum (ex. high-strength

[12] Hydrogen sulphide is a flammable and extremely hazardous gas and the exposure to low concentration can cause respiratory system irritation, breathing difficulties and other complaints.

gypsum, water and foaming agents) (Boccarusso et al., 2020), lightweight gypsum products from industrial and urban wastes (ex. Cork–gypsum composite) (Sair, Mandili, Taqi, & El Bouari, 2019), and smart gypsum composites (produced with the addition of microcapsules containing phase change materials (PCMs)) (Jia et al., 2021; Lushnikova & Dvorkin, 2016).

3.1.10 Sealants and Adhesives

Sealants and adhesives are essential components of modern buildings. They form a relatively small percentage of products consumed in construction. It has been estimated that more than 20% of the adhesives and sealants produced worldwide are used in the construction industry (S. Magalhães et al., 2019). They have been utilized to join various building materials and components and also to stop water, air, sound, dust, insects and other substances from passing through material surfaces, joints, or openings. Another main feature of these products is their ability to withstand extension and compression when the building parts thermally expand and contract (Hutchinson & Iglauer, 2006). Thus, they must be able to resist severe environmental conditions for a long period. Sealants are frequently used to seal joints between building materials and components while adhesives are often utilized to join two substrates (S. Magalhães et al., 2019).

Typically, sealants offer lower strength and high expansion in comparison to adhesives which offer a more rigid and durable performance. These materials play a major role in the air and water tightness as well as the energy efficiency of the buildings (Fufa, Labonnote, Frank, Rüther, & Jelle, 2018). Generally, two types of adhesives are used in construction including non-structural and structural adhesives. The structural adhesives are used as bonding for structural parts such as structural glass, metal bonding, and composite bonding. The non-structural adhesives, on the other hand, are used to bond materials or parts that do not need very high strength; for example, decorative materials, particle boards, panels, etc.

Sealants and adhesives can be composed of several chemicals such as silicones, urethanes, acrylics, silicones, and a group of polymers (Chew & Guan, 1999). However, they normally contain volatile organic compounds (VOCs) and other hazardous substances that are harmful to both the health of human beings and the environment. For instance, most of the sealants emit potentially toxic VOCs into indoor air (Kubba, 2017). Besides, these materials are unrecyclable, non-biodegradable, and normally disposed of as part of the element to which they are attached. Furthermore, negative environmental impacts have been associated with their disposal.

Moreover, the manufacturing of these materials consumes large amounts of energy and generates huge quantities of emissions. The majority of life cycle energy consumption takes place during the production phase (A1-A3)[13]. Generally, sealants and adhesives have an average embodied energy of 100 MJ/kg and embodied carbon of 4 $kgCO_2$/kg. For instance, the total use of non-renewable primary energy resources during the manufacturing stage (A1-A3) of silicone-based construction sealants has reached a figure of 135 MJ/kg and the global warming potential of 7.08 $kgCO_2$-eq/kg (Institut Bauen und Umwelt e.V. (IBU), 2016). In light of this, the search for responsible alternatives to conventional adhesives is of a fundamental need.

The sustainability identifications of sealants, adhesives and fillers are greatly overlooked in the construction industry and very little information is available regarding the assessment of their environmental impacts. However, as a general role, solvent-free products, do not off-gas, and meet the acceptable volatile organic compound (VOC) level are considered sustainable alternatives. Recently, water-based adhesives and renewable polymers (Bio-based adhesives and sealants) have been introduced as sustainable alternatives to petroleum-based feedstock. The absence of solvents ensures less or no VOC emissions and hazardous chemicals released during the application and curing while the use of bio-based materials guarantees reduced carbon footprint of the products.

Table 3-9 shows some of the alternatives to substitute petrochemically derived adhesives and sealants.

Alternative sealants and adhesives	Methods/Strategies/Materials	Reference (s)
Polymers obtained from renewable animal and plant-based sources (biopolymers)/ water-based adhesives (waterborne adhesives)	**Starch**, **lignin**, **natural rubber**, **gelatin-based glues**, **plant oils**, and **cellulosic adhesives** (produced without using harmful chemicals and organic solvents/ water is used for all the polymerization and treatment processes. The strength of the adhesive is reached when water is naturally evaporated or absorbed by the substrate).	(Addis, Koh, & Gordon, 2020; Ang, Ashaari, Lee, Md Tahir, & Halis, 2019; Arias, González-García, González-Rodríguez, Feijoo, & Moreira, 2020; Heinrich, 2019; Mabrouk, Dufresne, & Boufi, 2020; S. Magalhães et al., 2019; Packham, 2014; H. Yin et al., 2020).

Table 3-9: Possible alternatives to substitute traditional adhesives and sealants

[13] A1= Raw material supply, A2= Transport, A3= Manufacturing.

3.2 Chapter Summary

This chapter aimed to create a benchmarking of sustainability to review current practices and advances of various construction products. A systematic review of the relevant literature was conducted to categorize and summarize the environmental impacts of common building materials used in the construction industry with a more focus on the products integrated into the building facade assemblies. It is directed towards identifying the key indicators used for measuring sustainable construction materials.

This chapter showed that the current utilization of conventional building materials has been linked with four major impacts include the massive consumption of natural resources and non-renewable energy, greenhouse gases emissions, and huge waste production. The literature proved that raw materials substitution and by-products integration, recycling of construction and demolition wastes, using prefabricated building products and components, and design for reuse and recycling are the most common strategies that considered to reduce the environmental impacts of construction products.

Generally, products that are manufactured using non-toxic natural or renewable resources and, alternatively, pre-consumer and post-consumer waste-based materials are considered sustainable options. In this matter, the usage of bio-based construction materials to fully or partially replace conventional materials has been examined extensively in recent studies, which shows their potential in developing sustainable construction materials in the coming decade. Also, the composite or multi-functional materials were introduced as an emerging approach towards advancing processes and products and create several paths to increasing materials sustainability and to overcoming the challenges which the construction industry is encountered. However, these materials are recognized to be the most difficult to disassemble and require high energy to process.

The literature studied in this chapter showed that a significant amount of recent developed studies is a primary focus on the energy and carbon emissions of building materials, and the cradle to gate is the boundary system used in most of the studies. This signifies that embodied energy and embodied carbon are becoming primary indicators of materials sustainability. Furthermore, the end-of-life options were considered a key factor in determining the overall life cycle impact of building products. In this manner, recyclable technology was considered the most commonly used approach to close the material resource loop and it is available for many construction products, though its worldwide application is still limited.

CHAPTER 4: BUILDING ENVIRONMENTAL ASSESSMENT TOOLS

September 2021

4. CHAPTER FOUR: BUILDING ENVIRONMENTAL ASSESSMENT TOOLS

4.1 General Overview

The construction stakeholders started to recognize the negative impact of the buildings on the environment since the 1990s. However, the need for environmentally friendly products and services has led to increased demand for environmental assessment tools to evaluate their impact. These tools have been developed by various institutes and developers for different purposes. For example, they can be used for research and to support decision making. The building research establishment environmental assessment tool (BREEAM) was the first building assessment tool established by the UK in 1990, and after that time, many tools have been introduced all over the world. These tools can be employed to evaluate various environmental impacts of a product throughout the building's life cycle, yet they can be used at global, national and local levels for different purposes (Haapio & Viitaniemi, 2008).

Nowadays, there are many building assessment tools such as Leadership in Energy and Environmental Design (LEED, United States), BRE Environmental Assessment Method (BREEAM, United Kingdom), Green Building Council of Australia Green Star (GBCA, Australia), Green Mark Scheme (Singapore), Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB, Germany), Comprehensive Assessment System for Built Environment Efficiency (CASBEE, Japan), Pearl Rating System for Estidama (Abu Dhabi Urban Planning Council), the evaluation standard for green building (ESGB, China), Hong Kong Building Environmental Assessment Method (HK-BEAM), Green Building Index (Malaysia), Living Building Challenge (LBC) and more (Zuo & Zhao, 2014) (See **Figure 4-1**). However, these tools are covering various aspects of sustainability and a number of credits and points are available under each category and the total of the credits or points are used to determine the overall performance of the building, thus the rating system differs from one project to another.

Additionally, occupying these tools and their rating systems in design projects will ensure the construction of more green buildings as well as they will help in minimizing and optimizing the consumption of natural resources and control pollution (Doan et al., 2017). Buildings certified by those rating systems are believed to be less energy consumption and provide a better living environment for their users (S. ; Y. T. Yu, 2011).

In this chapter, a detailed review will be carried to analyze and categorize the existing environmental assessment tools[14] in order to see the differences between them in terms of their practical use when evaluating the environmental performance of building materials. In real practice, there are many existing environmental assessment tools, although most of the investigated tools in this study are internationally well known and some of them can be used at a global level such as BREEM, LEED, CASBEE, BEAM Plus, Green Star, and LBC.

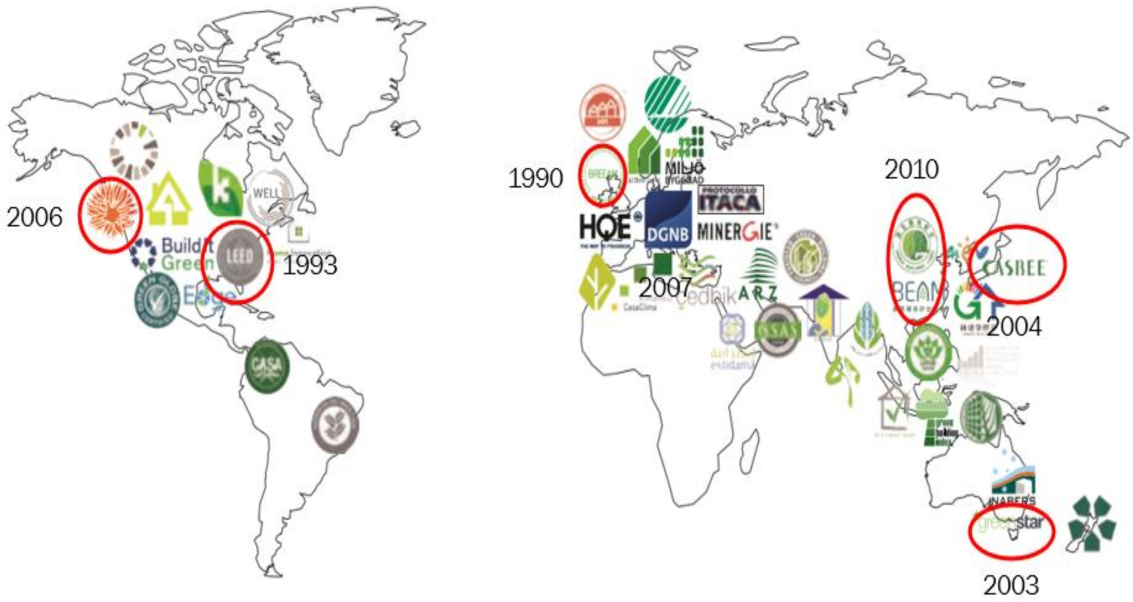


Figure 4-1: Environmental Assessment Certifications and their original location

4.1.1 BRE Environmental Assessment Method (BREEAM)

The Building Research Establishment Environmental Assessment Method (BREEAM) was the first environmental building rating system launched and operated by BRE (Building Research Establishment) in England in 1990. It was first adjusted to assess offices in 1993 (W. L. Lee, 2013), then it used to assess the environmental performance of individual buildings, communities and infrastructure projects (Shamseldin, 2018). The BREEAM was a pioneer in addressing various sustainability and environmental issues, and a broad range of nine environmental categories with different weights have been used for the measurement including Management, Health & Wellbeing, Energy, Transport, Water, Materials, Waste, Land Use & Ecology and Pollution. Besides, a new category called Innovation has been added to the BREEAM in order to support innovation within the construction industry and its supply chain. See **Table 4-1**

[14] More than 600 sustainability assessment rating systems are available worldwide.

BREEAM CLASS	WEIGHT
Management	11%
Health and Well-being	19%
Energy	20%
Transport	6%
Water	7%
Materials	13%
Waste	6%
Land use and Ecology	8%
Pollution	10%
Total	100%
Innovation (Additional)	10%

Table 4-1: Weights Percentages of BREEAM Classes

Note: The level of achievement of each class verifies the percentage total for the assessment, and the final score is 100%.

Many versions of BREEAM have been released for certifying projects and up to date, the BREEAM international new construction 2016 is the latest version (Awadh, 2017). BREEAM is widely used in Europe and many parts of the world and as of February 2019, BREEAM had certified over 567,000 projects and 2.3 million registered projects in 81 countries. The final evaluation score is stated as a percentage over available total points as follow: 30% for Pass, 45% for Good, 55% for Very Good, 70% for Excellent, and 85% for outstanding classification. The pre-assessment stage is the first evaluation stage in the certification process in which a predicted score is estimated by a pre-assessment estimator. Afterwards, at the early design stage, the project must be registered by an assessor who submits evidence for BREEAM for certification purposes. Finally, the assessment and certification of the project during the building lifecycle will be processed using BRE global lists (Z. Ding et al., 2018).

The assessment method of BREEAM starts by calculating the credits achieved under each environmental section, then the percentages of the credits achieved under each section are calculated (Compared to credits available). Next, the section score will be estimated via multiplying the credits percentages by the weights assigned for each environmental section. Finally, the overall score of the project can be achieved by a total of the sections weighted scores. See **Table 4-2**

BREEAM Section	Credits Achieved	Credits Available	% of Credits Achieved	Section Weighting (fully fitted)	Section Score
Management	10	20	50.00%	0.12	6.00%
Health and Well being	17	21	80.95%	0.14	11.33%
Hazards	1	1	100.00%	0.01	1.00%
Energy	16	34	47.05%	0.19	8.94%
Transport	5	11	45.45%	0.08	3.63%
Water	5	9	55.56%	0.06	3.33%
Materials	10	14	71.435	0.125	8.92%
Waste	3	13	23.07%	0.075	1.73%
Land use and ecology	5	5	100.00%	0.10	10.00%
Pollution	9	12	75.00%	0.10	7.44%
Innovation	2	10	20.00%	0.10	2.00%
Final BREEAM score					**64.32%**
BREEAM Rating				**VERY GOOD**	

Table 4-2: Example of BREEAM Score and Rating Calculation System

Last but not least, BREEAM has been worked as a base model for many rating themes in Canada, New Zealand, Norway, Singapore and Hong Kong. BREEAM is a widely used tool and it accounts for 80% of the sustainable building certification share of the European market (Collins, Junghans, & Haugen, 2016). According to Vimpari and Junnila (2014), BREEAM certified buildings could consume 6–30% lower energy costs than non-certified buildings.

4.1.1.1 Building Materials Assessment and Credits in BREEAM

In addition to the nine BREEAM environmental categories, the second level of 57 individual assessment issues is presented in BREEAM international new construction 2016. However, for the materials part, this category supports steps taken to reduce the impact of construction materials through design, construction, maintenance and restoration. The use of materials accounts for approximately 13% of the total percentages a building can receive for BREEAM certification, which is the highest third weighting among other environmental sections. The total weight of the materials in BREEAM has been distributed into six subheadings. See **Table 4-3**

Symbol	Issue	Credits	Credits Summary
Mat 01	Life cycle impacts	Up to 6	Reductions in the building's environmental life cycle impacts through assessment of the main building elements.
Mat 02	Hard landscaping and boundary protection	N/A	-
Mat 03	Responsible sourcing of construction products	4	- Materials sourced following a sustainable procurement plan. - Key building materials are responsibly sourced to reduce environmental and socio-economic impacts.
Mat 04	Insulation	N/A	-
Mat 05	Designing for durability and resilience	1	- The building incorporates measures to reduce impacts associated with damage and wear and tear. - Relevant building elements incorporate appropriate design and specification measures to limit material degradation due to environmental factors.
Mat 06	Material efficiency	1	Opportunities and measures have been identified and taken to optimise the use of materials.

Table 4-3: Building Materials sub-category Credits and Summary in BREEAM

Evidently, life cycle impacts and responsible sourcing of materials subdivisions have the highest available credits with 50% and 33%, respectively. However, they are considered the most important issues under the material section. Consequently, promoting the use of low impact building materials from a responsible source will help in achieving higher credits under this section. See **Figure 4-2**

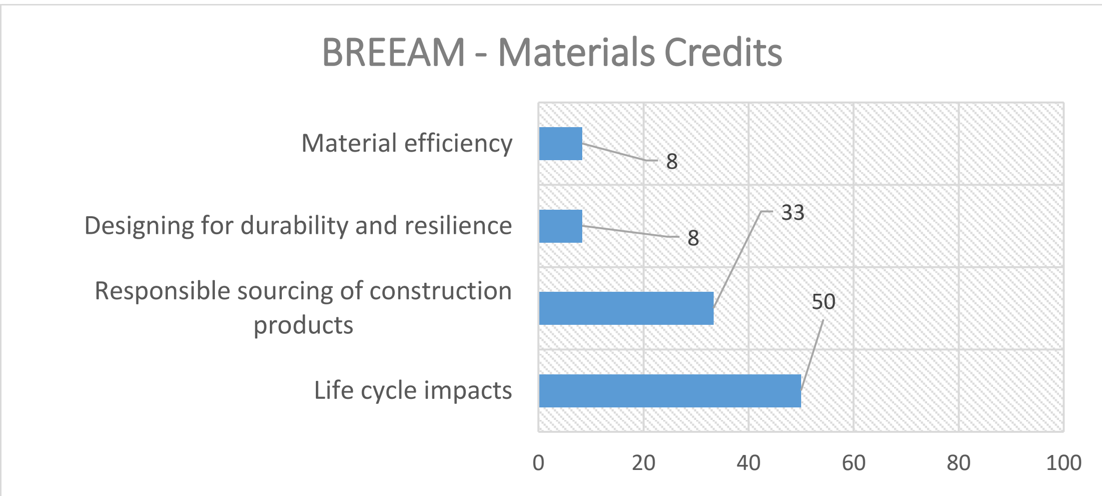


Figure 4-2: Building Materials Sub-Category Credits Percentage-BREEAM

Furthermore, the 6 credits available under the life cycle impacts category can be obtained by evaluating the environmental impacts of building materials by using BREEAM Mat 01 calculator and by reporting the life cycle greenhouse gas emissions for each material based on a 60-year building lifespan. Also, an additional 3 innovation credits can be achieved by completing a full life cycle assessment using an IMPACT LCA tool[15]. Additionally, Mat 02 (Hard landscaping and boundary protection) and Mat 04 (Insulation) are not assessed as a standalone issue, but combined within Mat 01 (life cycle impacts) and Mat 03 (responsible sourcing products).

On the other hand, the Mat 05 sub-category (Designing for durability and resilience) aimed to promote acceptable protection of external building elements and landscape, hence enhancing the durability and maximizing materials optimization. Similarly, Mat 06 (Material efficiency) meant to reduce the environmental impacts of materials use and waste by optimizing efficiency and promoting environmental measures for the building materials throughout their lifetime.

4.1.2 Leadership in Energy and Environmental Design (LEED)

LEED was developed by the United States Green Building Council (USGBC) for the US Department of energy and the first version (LEED v1.0) launched in 1998 (began its implementation in 2000). Up-to-date, LEED v4.0 is the last version released in 2014. LEED is considered the most widely implemented environmental rating scheme in the world. At present LEED was used in over 90,000 projects across 165 countries and territories. The last version of LEED consists of nine evaluation categories including Integrative process, location & transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor environmental quality, Innovation and Regional Priority.

Moreover, LEED covers almost all types of buildings and all building phases including new construction, interior fit-outs, operations and maintenance, homes and neighbourhoods. Firstly, LEED for building design and construction (BD+C) is related to New Construction, Core & Shell, Schools, Retail, Hospitality, Data Centers, Warehouses & Distribution Centers, and Healthcare. Secondly, LEED for interior fit-outs projects includes commercial interiors, retail and hospitality. Furthermore, LEED for Building Operations & Maintenance (O+M) is applied to existing buildings that are

[15] A spreadsheet-based calculator required to determine whether a project has used an appropriate LCA tool, and to calculate the number of credits achieved for this BREEAM issue, based on the scope and rigour of life cycle assessment and elements considered within the LCA.

undergoing improvement work concerning Existing Buildings, Schools, Retail, Hospitality, Data Centers, and Warehouses & Distribution Centers. The fourth sector is the LEED for Neighborhoods development which is related to new land development projects or redevelopment projects including residential uses, nonresidential uses, or mixed-use. The last sector is the LEED for homes design and construction which is applied to single-family homes, low-rise or mid-rise multifamily.

Moreover, LEED uses points to evaluate projects and it has four rating levels based on the achievable points: 40-49 points (certified level), 50-59 (silver), 60-79 (gold) and 80 points or more (platinum). The process of achieving LEED certification looks relatively straightforward, the number of points the project earns verifies its level of LEED certification. However, within each of the LEED categories, the project must satisfy certain prerequisites and earn points. Prerequisites are required elements or green building strategies that must be included in any LEED-certified project while the credits are optional elements that may vary from one project to another in order to get LEED certification (Uğur & Leblebici, 2018). See **Table 4-4**

LEED 4 Categories	**LEED for (BD+C)**	**LEED for (ID+C)**	**LEED for (O+M)**	**LEED for homes design and construction**	**LEED for (N+D)**
Integrative Process	1	2	-	2	Smart location and linkage 28
Location and Transportation	16	18	15	15	
Sustainable Sites	10	-	10	7	Neighbourhood pattern and design 41
Water Efficiency	11	12	12	12	
Energy and Atmosphere	33	38	38	38	Green infrastructure and building 31
Materials and Resources	13	13	8	10	
Indoor Environmental Quality	16	17	17	16	Innovation and design process 6
Innovation	6	6	6	6	
Regional Priority	4	4	4	4	Regional priority credits 4
TOTAL	**110**	**110**	**110**	**110**	**110**

Table 4-4: Environmental Categories and their Credits and Points in LEED v4

Additionally, four main steps are required to LEED certification including the registration of the project by completing key forms to ensure that the project meets the basic LEED requirements, applying for LEED certificate by submitting the appropriate documentation to the Green Building Council Institute (GBCI) to review the project, then the GBCI will conduct a technical review and finally the review results and the certification decision will be received. An integrated design approach can be promoted by using the LEED green rating system which supposed to reduce energy use, improve indoor air quality and achieve the overall sustainability of the project. According to Newsham et.al, on average LEED-certified properties consume 18–39% lower energy usage than non-certified properties (Newsham, Mancini, & Birt, 2009).

4.1.2.1 Building Materials Assessment and Credits in LEED

Materials and resources are one of the nine green building categories adopted in the LEED rating system. The utilization of materials and resources accounts for approximately 11% of the points a building can gather for LEED v4 certification (Gurgun, Komurlu, & Arditi, 2015). However, LEED v4 focus on reducing the embodied energy of the building materials and other environmental impacts associated with material's extraction, manufacturing, transport, maintenance and disposal. The proposed credits under this section are intended to encourage the use of locally produced building materials, recycling and optimization concepts as well as improve performance and promote resource efficiency. See **Table 4-5**

The life cycle impact reductions have been considered as one of the most important sub-categories in the materials and resources section with a 5 possible points score in LEED v4 for BD+C and 4 points in LEED v4 for ID+C. The life cycle assessment credits call for improving building life cycle impacts by a 10% reduction compared to a baseline building[16]. Moreover, LCA must be evaluated for six environmental impact categories including global warming potential, depletion of the stratospheric ozone layer, acidification of land and water sources, eutrophication[17] , the formation of tropospheric ozone and depletion of nonrenewable energy resources. Furthermore, an additional innovative point for the LCA can be achieved if the team shows an improvement over the required credits in the above six impact measures.

[16] The baseline and proposed buildings must be of comparable size, function, orientation and location.

[17] The process by which a body of water becomes enriched in dissolved nutrients (such as phosphates) that stimulate the growth of aquatic plant life usually resulting in the depletion of dissolved oxygen.

Materials and Resources Credits in LEED v4							
LEED for (BD+C)	**C.**	**LEED for (ID+C)**	**C.**	**LEED for (O+M)**	**C.**	**LEED for homes design and construction**	**C.**
Storage and Collection of Recyclables	Pr.	Storage and Collection of Recyclables	Pr.	Ongoing Purchasing and Waste Policy	Pr.	Certified Tropical Wood	Pr.
Construction and Demolition Waste Management Planning	Pr.	Construction and Demolition Waste Management Planning	Pr.	Facility Maintenance and Renovations Policy	Pr.	Durability Management	Pr.
Building Life-Cycle Impact Reduction	5	Long-Term Commitment	1	Purchasing-Ongoing	1	Durability Management Verification	1
Building Product Disclosure and Optimization - Environmental Product Declarations	2	Interiors Life-Cycle Impact Reduction	4	Purchasing-Lamps	1	Environmentally Preferable Products	4
Building Product Disclosure and Optimization - Sourcing of Raw Materials	2	Building Product Disclosure and Optimization - Environmental Product Declarations	2	Purchasing-Facility Management and Renovation	2	Construction Waste Management	3
Building Product Disclosure and Optimization - Material Ingredients	2	Building Product Disclosure and Optimization - Sourcing of Raw Materials	2	Solid Waste Management-Ongoing	2	Material Efficient Framing	2
Construction and Demolition Waste Management	2	Building Product Disclosure and Optimization - Material Ingredients	2	Solid Waste Management-Facility Management and Renovation	2		
		Construction and Demolition Waste Management	2				
Total Credits	**13**		**13**		**8**		**10**

Table 4-5: Materials and Resources credits and points in LEED v4

Furthermore, LEED v4 promotes the use of materials and products that were extracted, processed, and manufactured locally as well as encouraging the use of Environmentally

Preferable Products (EPP) and services to reduce the negative impact on human health and the environment. For this purpose, up to 5 points can be achieved by utilizing environmental preferable materials in homes design. Also, the Construction and demolition waste management are worth up to 3 points in building materials and resources of LEED v4. The purpose of this credit is to redirect the construction and demolition disposal of building materials from the landfill to manufacturing, reusable and recycling processes to appropriate sites.

On the other hand, the building product disclosure and optimization (BPDO) concept has been introduced in LEED v4 to cover three main areas include environmental product declarations[18], sourcing of raw materials, and material ingredients (products' chemical inventory). Each one of the three requirements worth up to 2 points. The categories under this part are intended to encourage the use of materials for which life cycle data are available and to select materials and products which their environmental, economic and social life cycle impacts have verified. The two points under this category can be achieved individually or jointly. One point can be achieved if the project uses twenty or more different products with EPDs from five or more different manufacturers, while a second point is available for the use of materials that verified with EPDs to fall below industry average in three of the six impact categories which mentioned earlier (Gelowitz & McArthur, 2018). See **Figure 4-3**

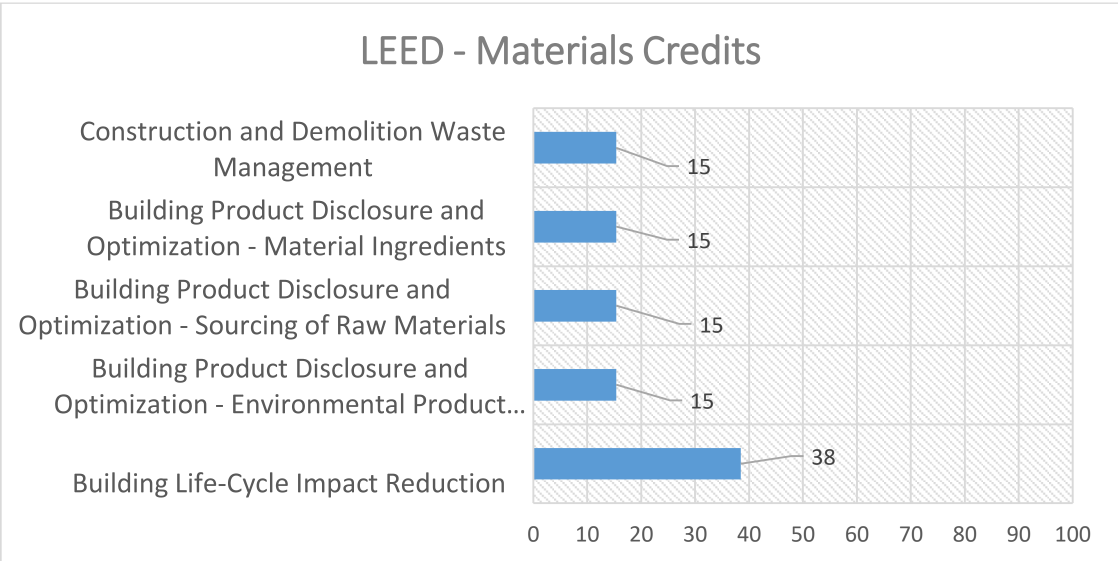


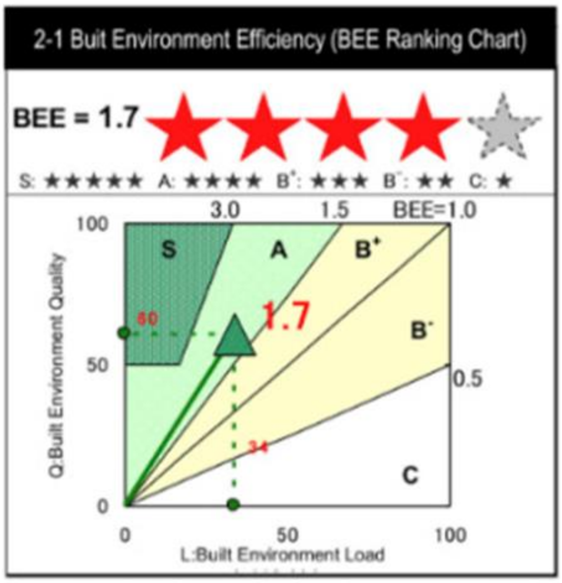
Figure 4-3: Building Materials Sub-Category Credits Percentage-LEED

[18] An Environmental Product Declaration (EPD) is a summary document that provides verified and comparable environmental information about goods and services.

4.1.3 Comprehensive Assessment System for Built Environment Efficiency (CASBEE)

The Comprehensive Assessment System for Built Environment Efficiency (CASBEE) is the first building environmental assessment method developed in Japan for the evaluation of sustainable building practices. CASBEE was established in 2001 by cooperation between government, industry and academia with the support of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) of Japan and it was firstly released as an architectural design tool (S. C. Wong & Abe, 2014).

Up to date, a decade after the introduction of CASBEE, its assessment system includes over 15 tools ranging from building to cities. CASBEE is consist of assessment tools adapted to different scales: construction (housing and buildings), urban (town development) and city management. These tools are communally known as the CASBEE Family. Each tool is intended for a specific purpose and target users and is designed to accommodate a wide range of building types. The number of certified buildings with CASBEE is still modest compared to other environmental assessment tools due to its limitation to the Japanese context (As of April 2015, the total number of CASBEE certified buildings is over 450). However, CASBEE released its first international version in 2015 for worldwide use which generates great attention amongst industries, governmental organizations and academics. Moreover, CASBEE has a unique and simple rating and assessment system that involves five grades: Superior (S), Very Good (A), Good (B+), Slightly Poor (B-) and Poor (C). See **Figure 4-4**



S: Excellent A: Very good B+: Good B-: Fairy poor C: Poor

Figure 4-4: Sustainability ranking by BEE in CASBEE

The assessment results are calculated differently in CASBEE. Instead of dividing credits into categories, CASBEE evaluates two spaces, external and internal, divided by the virtual boundary (Doan et al., 2017). Nevertheless, factors inside the boundary are evaluated by Q (Built Environment Quality) while factors outside the boundary are evaluated by L (Built Environment Load), then credits can be evaluated before putting on the BEE chart (Built Environment Efficiency) by using the formula: BEE= Q/L. The improvement of Q and reduction of L are included for building environmental assessment and they are only found in CASBEE. See **Figure 4-5.**

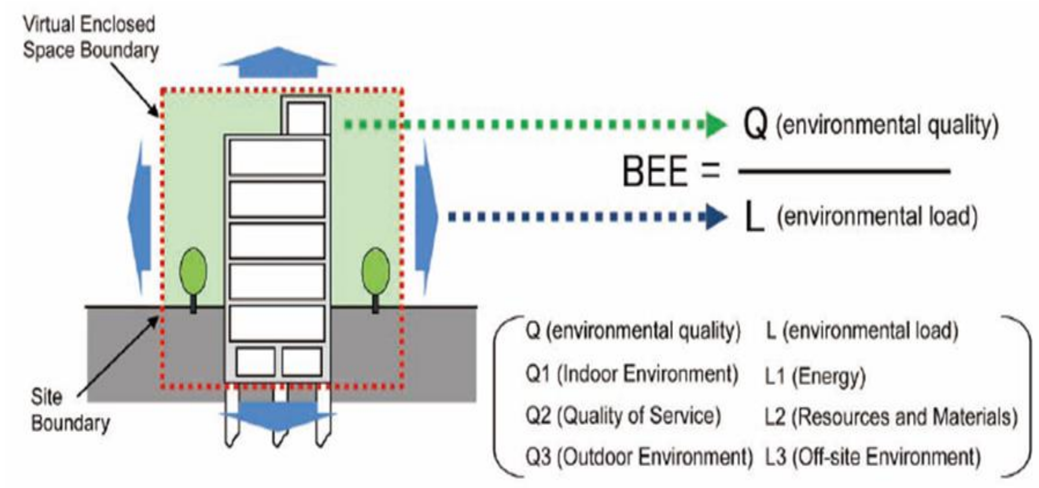


Figure 4-5: Division of the assessment categories in CASBEE

Adapted from (Doan et al., 2017)

Q assesses improvement in living comfort for the building users, within the virtual enclosed space while L evaluates negative aspects of environmental impact which go beyond the virtual enclosed space to the outside. Therefore, a building with a higher BEE value (higher Q value and lower L value) is assessed to be more green. Additionally, the Q is further divided into three sub-categories for the assessment including Q1 (Indoor environment), Q2 (Quality of service), and Q3 (Outdoor environment). Correspondingly, L is divided into L1 (Energy), L2 (Resources and Materials), and L3 (Off-site environment). See **Table 4-6**

Category	Indoor Environment	Quality of Service	Outdoor Environment (on-site)	Energy	Resources and Materials	Off-site Environment
Weight %	20	15	15	20	15	15
	Q (Built Environment Quality)			**L (Built Environment Load)**		

Table 4-6: Environmental Categories and their Weights in CASBEE

However, four assessment fields are covered in CASBEE include Energy Efficiency, Resource efficiency, Local environment, and Indoor environment. These assessment tools can be applied within the set of the architectural design process, starting from the preliminary design stage and continuing through developed design and post-design stages (Ikaga, 2013). Since 2010, a separate star rating system is given for the performance of life cycle carbon emissions (LCCO2) in buildings, where: 5 stars = LCCO2 below 30% (zero energy consumption achieved during building operation), 4 stars= LCCO2 below 60% (50% energy savings achieved during building operation), 3 stars= LCCO2 below 80% (30% energy savings achieved during building operation), 2 stars= = LCCO2 below 100% (current energy efficiency standards are satisfied), and 1 star= = LCCO2 over 100% (non-efficient energy building).

4.1.3.1 Building Materials Assessment and Credits in CASBEE

The materials and resources category in CASBEE has 15% weights which are coming after those of Q1 (indoor environment) and L1 (energy). On the other hand, it’s similar to the weights of Q2 (quality of service), Q3 (outdoor environment-on-site), and L3 (off-site environment). Besides, there are 13 items (13/98 items) included under the materials and resources category of CASBEE which represent about 13% of the total items. Commonly, the CASBEE materials category is aspired to minimize the negative environmental impacts during the building lifetime by minimizing the carbon and energy embodied impacts, improving indoor air quality, enhancing building performance and resource efficiency as well as extending the lifespan of the material.

Furthermore, the L2 (resources and materials) contains three main categories, the first category is the water resources which has two sub-categories including water-saving, and rainwater and greywater. The second category (Reducing the use of non-renewable resources) has six sub-items including reducing the use of materials, continuing use of existing structural frames, etc., use of recycled materials as structural materials, use of recycled materials as non-structure materials, timber from sustainable forestry, and efforts to enhance the reusability of components and materials. The third category (Avoiding the Use of Materials with Pollutant Content) has two sub-items; use of materials without harmful substances and elimination of CFCs and Halons. These two items are included to evaluate the pollutants and reduction of chemicals such as volatile organic compounds (VOCs), metallic compounds, etc. Besides, the protection of the ozone layer. See **Table 4-7**

		Weight (%)	Main Category	Sub-category
L2	Resources & Materials	15	Water Resources	Water-Saving
				Rainwater and Grey W
			Reduce Use of Non-renewable Resources	Reducing Use of Materials
				Continuing Use of Existing Structural Frames, etc.
				Use of Recycled Materials as Structural Materials.
				Use of Recycled Materials as Non-structural Materials.
				Timber from Sustainable Forestry.
				Efforts to Enhance the Reusability of Components and Materials.
			Avoiding the Use of Materials with Pollutant Content	Use of Materials without Harmful Substances.
				Elimination of CFCs and Halons.

Table 4-7: Materials-related criteria in CASBEE

4.1.4 Hong Kong Building Environmental Assessment Method (BEAM)

The Hong Kong Building Environmental Assessment Method - BEAM Plus (formerly known as HK-BEAM) was launched in December 1996 to offer independent assessments of building sustainability performance (X. Chen, Yang, & Zhang, 2017). The scheme covered a wide range of issues related to the impacts of buildings on the environment and includes two assessment methods, which cover new and existing office buildings (J. K. W. Wong & Kuan, 2014). BEAM plus consists of four assessment tools, namely New Buildings, Existing Buildings, Interiors, and Neighborhood, covering the whole building life cycle. Since 2010, over 300 BEAM plus projects are certified (The Hong Kong Green Building Council, n.d.). The most current BEAM plus documents were released in 2012 (BEAM plus for new and existing building v1.2), 2013 (BEAM plus for interior v1.0), and 2016 (BEAM plus existing building v 2.0). They created to encouraging the adoption of green building management and upgrading the building services systems towards sustainability.

Moreover, various assessment aspects have been covered by BEAM including community aspects, site aspects, green building attributes, management, materials and waste aspects, energy use, water use, indoor/outdoor environmental quality, and innovations and additions. For example, six assessment categories are covered by BEAM plus for New Buildings including site aspects (22+3B), materials aspects (22+1B), energy use (42+2B), water use (9+1B), indoor environmental quality (32+3B), and innovations and additions (1+5B). At this point, “B” stands for bonus credits and different criteria are used for different building types (W. L. Lee, 2013). Also, BEAM plus allocated credits to each assessment criterion by analysing the weighting and rating techniques used in similar assessment methods (BREAM and LEED). However, the assigning weights are built up following the significant impact of each criterion. See **Table 4-8**

Category	**Weighting (%)**	**Credits**
Site Aspects (SA)	25	22+3B
Materials Aspects (MA)	8	22+1B
Energy Use (EU)	35	42+2B
Water Use (WU)	12	9+1B
Indoor Environmental Quality (IEQ)	20	32+3B
Innovations and Additions (IA)		1+5B
Total	**100**	

Table 4-8: Credit weightings and the overall grade of BEAM plus for NC. v1.2

The BEAM assessment process is undertaken by an independent BEAM assessor engaged by the BEAM society limited[19]. Buildings can be assessed at any time, but it is recommended to start the assessment from an early design stage to allow changes during different design stages which in turn will improve the overall performance of the examined building. The assessment process starts by registering the project, then an assessment agreement must be signed with BEAM society limited, afterwards, the project will be assessed by the BEAM assessor and reviewed by a technical review committee. In the last two stages, the rating will be given to the applicants and HKGBC issues the certificate.

BEAM plus can be used to evaluate new buildings, existing buildings, fit-out works and interior, and neighbourhood. For example, BEAM plus for new building certification v1.2 can be used for the evaluation of all buildings including, but not limited to, offices, retail, catering and service establishments, libraries, educational establishments, hotels and residential apartment buildings. Moreover, Credits are given on the six mentioned categories according to performance or feature specific criteria, then counted together to make the final score. However, there are five scores in BEAM plus; bronze (≥40%

[19] An independent not-for-profit organization whose membership is drawn from many professional and interest groups in Hong Kong’s building construction and real estate sectors.

credits), silver (≥55% credits), gold (≥65% credits) and platinum (≥75% credits). Also, the project must obtain a minimum percentage of credits (for the six categories) to be qualified for the award. See **Table 4-9**

PLATINUM 鉑金級 V1.2 2017 HKGBC BEAM Plus 綠建環評	GOLD 金級 V1.2 2017 HKGBC BEAM Plus 綠建環評	SILVER 銀級 V1.2 2017 HKGBC BEAM Plus 綠建環評	BRONZE 銅級 V1.2 2017 HKGBC BEAM Plus 綠建環評
≥75% credits	≥ 65% credits	≥ 55% credits	≥ 40% credits

Table 4-9: The four rating schemes of BEAM plus

4.1.4.1 Building Materials Assessment and Credits in BEAM Plus

BEAM plus Materials Aspects include the selection of materials, efficient use of materials, and waste disposal and recycling. However, various credits and points of materials have been assigned within various BEAM plus family (BEAM Plus Neighborhood (ND), BEAM Plus New Buildings (NB), BEAM Plus Existing Buildings (EB), and BEAM Plus Interiors (BI). Moreover, a prerequisite for the materials aspect has been set out to make sure that the project applies the basic minimum requirement needed to reduce environmental impacts through improved design, choice of materials, and installation methods. See **Table 4-10**

In BEAM plus new building v1.2, 4 prerequisites, 11 sub-categories and 22 credits have been included in the material section. However, the four minimum requirements including the use of non-CFC based refrigerants, non-virgin timber used for temporary works, implementation of construction/demolition waste management and provision of waste recycling facilities. Also, 3 prerequisites, 11 sub-items, and 26 credits are included in BEAM plus for interiors v1.0 which consider as an environmental assessment tool for interior spaces, including offices, shops, and related interior premises. Nevertheless, many similarities in materials sub-categories have been noticed in the above mentioned BEAM plus family.

Moreover, BEAM Plus for Existing Buildings aims to reduce the environmental impacts of built structures whilst improving quality and user satisfaction, mainly, energy efficiency and environmental performance. It assesses the actual performance of a building involving the management, operation and maintenance and might be initiated at any time during the operation life of the buildings, yet, 7 sub-categories, 2 prerequisites, and 11 credits are assigned under this section.

BEAM PLUS New Building v1.2	C.	BEAM PLUS Interiors v1.0	C.	BEAM PLUS for Existing Building v1.2	C.
The timber used for temporary works	P1	Use of Non-CFC Based Refrigerants	P1	Use of Non-CFC Based Refrigerants	P1
Use of Non-CFC based refrigerants	P2	Minimum Waste Recycling Facilities	P2	Waste Recycling Facilities	P2
Construction/ demolition waste management plan	P3	Timber Used for Temporary Works	P3	Building Reuse	1B
Waste recycle facilities	P4	Waste Recycling Facilities	2	Modular and Standardised Design	1
Building reuse	2+1 B	Interiors Components Reuse	3	Adaptability and Deconstruction	2+1 B
Modular and standardised design	1	Furniture and Partitions	3	Rapidly Renewable Materials	2
Prefabrication	2	Modular Design Materials	1	Sustainable Forest Products	1
Adaptability and deconstruction	3	Design for Disassembly	1	Ozone Depleting Substances	3
Rapidly renewable materials	2	Sustainable Flooring Products	4	Waste Management	2
Sustainable forest products	1	Sustainable Ceiling Products	4		
Recycled materials	3	Sustainable Wall and Door Products	4		
Ozone-depleting substances	2	Zero PVC	1		
Regionally manufactured material	2	Ozone Depleting Substances	1		
Demolition waste reduction	2	Demolition and Construction Waste Reduction	2		
Construction waste reduction	2				
Total Credits	**22+ 1B**		**26**		**11+ 2B**

Table 4-10: Summary of Credits in three BEAM Plus Family

On the other hand, materials and waste aspects of BEAM Plus neighbourhood v1.0 include building reuse and waste management. The section emphasizes the reduction of waste from a life cycle perspective, including site information design, and the necessities of properly designed waste facilities for waste recycling, recovery, and reuse. However, 2+1 bonus credit points appointed to the building reuse, while 3 credit points have been assigned for both minimized cut and fill and integrated waste management (a total of 8+1B credits points). See **Figure 4-6**

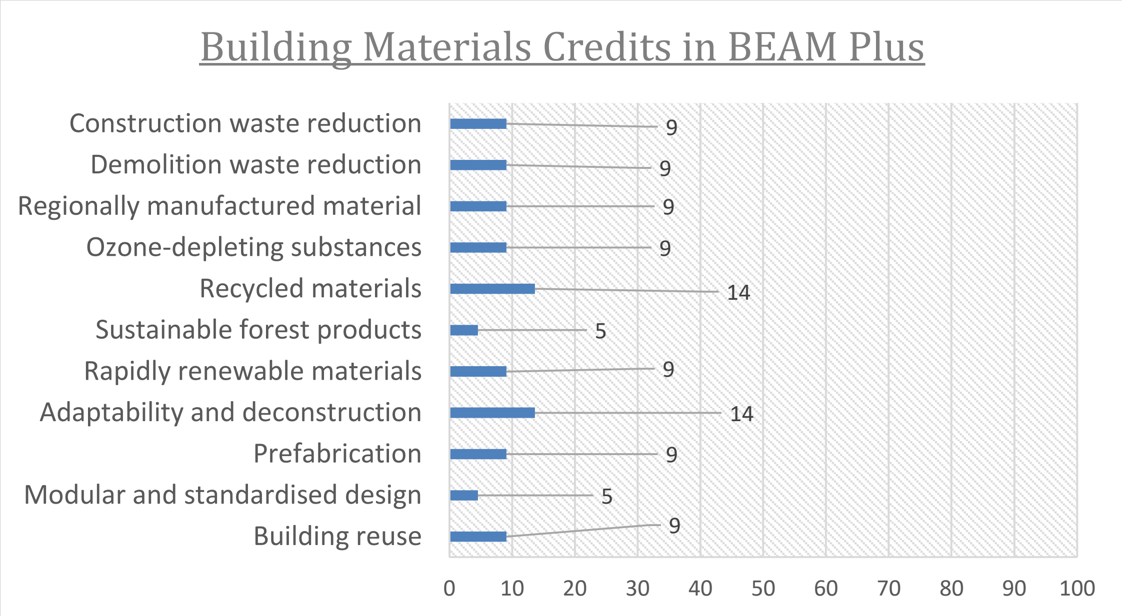


Figure 4-6: Building Materials Sub-Category Credits Percentage-BEAM Plus

<u>4.1.6 Green Building Council of Australia Green Star (GBCA)</u>

Green Building Council of Australia (GBCA) was launched in 2003 by the Green Building Council of Australia as a national and voluntary rating system for buildings and communities which is well known by Green Star. Australia is the world's largest contributor of greenhouse gas emissions and waste, thus the Green Star is aimed to improve environmental efficiencies of buildings, while increasing productivity, creating jobs and enhancing health and well-being (Z. Ding et al., 2018). Currently, over 2000 projects have been certified by green star certification. Green Star buildings are expected to produce 62% fewer greenhouse gas emissions, consume 51% less potable water, use 66% less electricity, and recycle 96% of their construction and demolition waste than average Australian buildings (Green Building Council of Australia, n.d.).

Also, five steps are included in certification starting with project registration, documentation (to demonstrate that the building meets Green Star's sustainability benchmark), submission (documentation to the GBCA for assessment), Assessing (an independent panel of sustainable development experts will review and assign the overall building score), and finally, the certification is awarded as third-party verification of a project's sustainability. The scheme is based on a rating system of collecting points and credits and it applies to a wide range of building types. For each credit, which is allocated into its specific category, a maximum number of 100 points can be achieved plus 10 additional innovation points. The certification is expressed as a number of stars: 10-19 points for I Star-Minimum Practice, 20-29 points (2 Star-Average Practice), 30-44 points (3 Star- Good Practice), 45-59 points (4 Star-Australian Best Practice), 60-74 points (5 Star-Australian Excellence), and finally, 75 and more points allow to obtain the 6 stars rating, that is the World leadership grade. See **Table 4-11**

Green Star Rating System	**Total Score Targeted Points**
I Star-Minimum Practice	10-19
2 Star-Average Practice	20-29
3 Star- Good Practice	30-44
(4 Star-Australian Best Practice	45-59
5 Star-Australian Excellence	60-74
World leadership	≥70

Table 4-11: Green Star Rating Schemes

Furthermore, the Green Star rating system measures the sustainability of buildings at all stages of the built environment lifecycle. Four rating tools are available for the certification including Green Star-Communities, Green Star-Design & As-Built, Green Star-Interiors, and Green Star-performance. Green Star – Communities assesses the planning, design and construction of large scale development projects at a district, neighbourhood and/or community scale (five assessment categories), and the current version of the rating tool is Green Star-Communities V 1.1 which was released in September 2016. Secondly, Green Star – Design & As-Built evaluates the sustainability results from the design and construction of new buildings or major renovations, across nine impact categories, and the last version is Green Star-Design & as Built v1.2 released in July 2017.

The third rating systems are the Green Star-Performance which established to assess the operational performance of buildings through nine impact categories, and the last version is Green Star-Performance v1.2 which released in November 2017. Green Star – Interiors is the last Green Star rating system focusing on the assessment of the sustainability outcomes of interior fit-outs across nine holistic impact categories, and the last version is Green Star-Interiors v1.2 released in July 2017. See **Table 4-12**

Green Star-Communities		Other Green Star Impact Categories –Available Points			
Category	**Points**	**Category**	**Design & As-Built**	**Interiors**	**Performance**
Governance	28	Management	14	13	17
Liveability	22	Indoor Environment Quality (IEQ)	17	23	18
Economic prosperity	21	Energy	22	20	24
Environment	29	Transport	10	7	7
		Water	12	5	12
		Materials	**14**	**24**	**10**
		Land use and Ecology	6	5	6
		Emissions	5	3	6
Innovation	10	Innovations	10	10	10
Total Points	100	Total Points	100	100	100

Table 4-12: Green Star Categories Scorecard

4.1.6.1 Building Materials and Assessment Credits in Green Star

The Green Star Materials category comprise credits and points that facilitate the efficient use and management of building and materials. It aims to address the consumption of materials that go into, or come out of, a building during the operational phase of its life cycle, through sustainable procurement and purchasing and the management of construction waste (waste from operations and refurbishments). In addition, it intends to encourage the selection of low-impact materials in order to reduce the consumption of resources during the whole lifetime of the building. Recently, GBCA developed some guidance related to life cycle assessment (LCA), environmental product declarations (EPD), and Best Practice Guidelines for PVC when submitting documentation with Green Star credits.

Moreover, the Materials category shared between 10-24 % of the total available points of the Green Star rating system in which 24 points have been noticed in Green Star-Interiors and 10 points in Green Star-Performance. Nonetheless, different sub-categories with various points have been included under each materials category. However, Life cycle impacts, responsible building materials, and construction and demolition waste are the most significant sub-categories included under the main schemes. See **Table 4-13**

Materials Category	Aims of the Credit/Selection	Credit Criteria	14 Points Available
Life Cycle Impacts	Prescriptive Pathway - Life Cycle Impacts/ Performance Pathway - Life Cycle Assessment	Comparative Life Cycle Assessment	0/6
		Additional Life cycle Impact Reporting	4
		Concrete	0/3
		Steel	0/1
		Building Reuse	0/4
		Structural Timber	4
Responsible Building Materials	To reward projects that include materials that are responsibly sourced or have a sustainable supply chain.	Structural and Reinforcing Steel	1
		Timber Products	1
		Permanent Formwork, Pipes, Flooring, Blinds and Cables	1
Sustainable Products	To encourage sustainability and transparency in product specification.	Product Transparency and Sustainability	3
Construction and Demolition Waste	Fixed Benchmark/ Percentage Benchmark	Fixed Benchmark	1
		Percentage Benchmark	

Table 4-13: Example of Green Star - Design & As-Built Scorecard

4.1.7 Living Building Challenge (LBC)

The living building challenge (LBC) is an ambitious certification and green building tool developed by Jason F. McLennan and Bob Berkebile and launched in 2006 by the Cascadia Green Building Coalition - a chapter of both the US and Canadian Green Building Councils. In 2009, the non-profit International Living Future Institute was created to manage certifications. The LBC administered by the international living future Institute (ILFI) and it can be used all around the world but is mainly used for buildings in North American on the east and west coasts. Considering that the LBC is performance-based, the guiding principles and performance metrics can be applied worldwide regardless of the location of the project and the climate zone of the country. As of April 2016 more than 331 projects have been verified by LBC (Living-Future, n.d.).

The ILFI described the tool as a philosophy that promotes the most advanced sustainability measurements in the built environment. It uses the metaphor of the flower to indicate that the built environment should have functioned as efficiently and cleanly as flowers. However, to achieve LBC certification, building most gives more than it takes by producing more energy than it uses, capturing and treating sufficient water, and be built using healthy materials. LBC can apply to any building projects include but not limited to new or existing buildings, single and multi-family residential, commercial and offices, hospitality and retail, medical and laboratory, and more. However, there are three typologies in LBC; Renovation, Landscape or Infrastructure (non-conditioned development), and Building.

The Living Building Challenge has two certification degrees; Living and Petal. The full living verification is very demanding and it can be compared to the highest levels of other internationally recognized certifications such as BREEAM Outstanding, LEED platinum, and DGNB platinum. However, to get the full living certification, all imperatives must be assigned to its typology (Petal). Generally, there are seven petals in the LBC system including Place, Water, Energy, Health, Materials, Equity and Beauty. Each Petal is further sub-divided into Imperatives (20 Imperatives), which address specific issues through detailed requirements. All twenty Imperatives are required for Buildings, sixteen for Renovations, and seventeen for Landscape + Infrastructure projects. If the project reaches three out of seven of these standards with at least one being either water, energy, or materials, then a petal certification can be received. In addition, imperatives 01 (Limits to Growth), and 20 (Inspiration + Education) are also required for Petal certification. See **Table 4-14**

In addition to petal and living certifications, a Net Zero Energy Building (NZEB) is also using the structure of the living building challenge to get the certification, and four of the LBC imperatives need to be attained to get the certification including imperative 01: Limits to Growth, 06: Net Positive Energy (reduced to one hundred per cent), 19: Beauty +Spirit, and 20: Inspiration + Education. The NZEB certification is based on actual performance rather than modelled outcomes. The process of achieving LBC certification is divided into three parts. The first part is the registration and fees payment. The second part is the documentation and operation phase. In this stage, all project's documents must be compiled and sent to the LBC institute, then the building must undergo a 12 months performance period to prove that the project meets the certification requirements. Part three is the audit and certification, in which, an auditor checks all submitted documents and performs a site inspection. However, if the projects meet the LBC criteria then the certification will be awarded.

	LIVING BUILDING CHALLENGE 3.1[20]			
	Buildings	Renovations	Landscape+ Infrastructure	
Place				01. Limits to Growth
	Scale Jumping		Scale Jumping	02. Urban Agriculture
	Scale Jumping	Scale Jumping	Scale Jumping	03. Habitat Exchange
				04. Human-Powered Living
Water	Scale Jumping	Scale Jumping	Scale Jumping	05. Net Positive Water
Energy	Scale Jumping	Scale Jumping	Scale Jumping	06. Net Positive Energy
Health + Happiness				07. Civilized Environment
				08. Healthy Interior Environment
				09. Biophilic Environment
Materials				10. Red List
	Scale Jumping	Scale Jumping	Scale Jumping	11. Embodied Carbon Footprint
				12. Responsible Industry
				13. Living Economy Sourcing
				14. Net Positive Waste
Equity				15. Human Scale + Human Places
				16. Universal Access to Nature + Place
	Scale Jumping	Scale Jumping	Scale Jumping	17. Equitable Investment
				18. Just Organization
Beauty				19. Beauty + Spirit
				20. Inspiration + Education
	(grey)	Imperative omitted from Typology	(orange)	Solutions beyond project footprint are permissible

Table 4-14: The Seven Petals and Twenty Imperatives of LBC v 3.1

[20] Living Building Challenge is a trademark of the International Living Future Institute (the Institute). The terms "Living Buildings," "Living Building," "Living Building Leader," "Living Future," and "Living Future Challenge" are also trademarks of the Institute

4.1.7.1 Building Materials and Assessment Credits in LBC

The materials section of the LBC aims to remove the dangerous known materials and practices and to derive construction towards a truly responsible building material. The LBC envisions a future where all materials in the built environment are responsible and have no negative impacts on human health and the environment. In 2014, the ILFI established a list of chemicals that are deemed harmful to include in materials. These banned materials cannot be used to obtain the Material Petal of the Living Building Challenge. However, 22 Materials are considered as red list materials such as Asbestos, Polyvinyl Chloride (PVC), Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs), Volatile Organic Compounds (VOCs) in wet-applied products, and more. See **Table 4-15**

RED LIST MATERIALS (Living Building Challenge[s] 3.1)	
• Alkylphenols	• Halogenated Flame Retardants (HFRs)
• Asbestos	• Lead (added)
• Bisphenol A (BPA)	• Mercury
• Cadmium	• Polychlorinated Biphenyls (PCBs)
• Chlorinated Polyethylene and Chlorosulfonated Polyethylene	• Perfluorinated Compounds (PFCs)
• Chlorobenzenes	• Phthalates
• Chlorofluorocarbons (CFCs) and Hydro chlorofluorocarbons (HCFCs)	• Polyvinyl Chloride (PVC)
• Chloroprene (Neoprene)	• Polyvinylidene Chloride (PVDC)
• Chromium VI	• Short Chain Chlorinated Paraffins
• Chlorinated Polyvinyl Chloride (CPVC)	• Wood treatments containing Creosote, Arsenic or Pentachlorophenol
• Formaldehyde (added)	• Volatile Organic Compounds (VOCs) in wet-applied products

Table 4-15: LBC Materials Red List

In addition, the project must account for the total embodied carbon impact of materials from its construction at least a one-time from an approved carbon offset provider. Similarly, third-party certified standards must be obtained for sustainable resource extraction and fair labour practices. Appropriate raw materials include stone and rock, metal, minerals, and timber. In the Third materials imperative (Living economy sourcing), the project must combine the use of local materials, incorporate place-based sustainable practices and solutions, and contribute to the expansion of the local economy.

Therefore, the following restrictions concerning the manufacturer location for materials and services must be applied to achieve Material Petal:

• 20% or more of the materials construction budget must come from within 500 kilometres of a construction site.

• An additional 30% of the materials construction budget must come from within 1000 kilometres of the construction site or closer.

• An additional 25% of the materials construction budget must come from within 5000 kilometres of the construction site.

• 25% of materials may be sourced from any location.

• Consultants must come from within 2500 kilometres of the project location.

The last Materials imperative is the Net Positive Waste. In this Imperative, the project team must do their best to minimize, optimize and eliminate the production of waste throughout the design, construction, operation and demolition stages for better conservation of natural resources. See **Table 4-16**

MATERIAL	MINIMUM DIVERTED/WEIGHT
Metal	99%
Paper and cardboard	99%
Soil and biomass	100%
Rigid foam, carpet, and insulation	95%
All others – combined weighted average	90%

Table 4-16: The required diversion percentage of wasted materials during construction

4.2 Chapter Summary

4.2.1 Building Environmental Assessment Tools

In this chapter, a comparative analysis of various building sustainability assessment tools was performed and the material-related issues were identified, classified, and summarized. Various environmental assessment tools are developed for the building sector worldwide, among these, the most recognized and accessible tools have been selected and investigated in this chapter. Most of these tools have been developed by research institutes. However, the examined tools are BREEAM International 2016, LEED v4.0, CASBEE international 2015, BEAM plus (Last versions 2012, 2013 and 2016), GBCA Green Star (versions 2016 and 2017), and LBC v3.1. See **Table 4-17**

	Organ.	Main categories	First v.	Last v.	Type of schemes	Rating level
BREEM (UK)	BRE	- Management - Health and well-being - Energy - Transport - Water **- Materials** - Waste - Land use and ecology - Pollution - Innovation	1990	2016	**BREEAM International** - BREEAM Inter. (NC) - BREEAM Inter. Refurbishment & Fit-Out - BREEAM Inter. In-Use - BREEAM Communities	- Unclassified - Pass - Good - Very good - Excellent - Outstanding
LEED (US)	USGBC	- Location and transport - Sustainable sites - Water efficiency - Energy and atmosphere **- Material and resources** - Indoor Environmental Quality - Regional priority - Innovation	1998	2014	**LEED version 4** - LEED-BD + C - LEED-ID + C - LEED - O + M - LEED-ND - LEED-Homes	- Certified - Silver - Gold - Platinum
CASBEE (Japan)	JSBC	- Indoor Environment - Quality of Service - Outdoor Environment (on-site) - Energy - Resources and Materials - Off-site Environment	2002	2015	**CASBEE Family** - CASBEE Housing Scale - CASBEE Building Scale - CASBEE Urban Scale - CASBEE City Scale	- Superior - Very Good - Good - Slightly Poor - Poor
BEAM plus (China)	HKGBC	- Site Aspects - Materials Aspects - Energy Use - Water Use - (IEQ) - Innovations and Additions (IA)	1996	2016	- BEAM Plus New Building - BEAM Plus Existing Building - BEAM Plus Interiors - BEAM plus Neighborhoods	- Bronze - Silver - Gold - Platinum

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	Organ.	Main categories	First v.	Last v.	Type of schemes	Rating level
Green Star (Australia)	GBCA	- Management - Indoor Environment Quality (IEQ) - Energy - Transport - Water - Materials - Land use and Ecology - Emissions - Innovations	2003	2017	- Green Star-Communities - Green Star-Design & As-Built - Green Star-Interiors - Green Star-performance	- I Star-Minimum Practice - 2 Star-Average Practice - 3 Star-Good Practice - 4 Star-Australian Best Practice - 5 Star-Australian Excellence - World leadership
LBC (US)	ILFI	- Place - Water - Energy - Health + Happiness - Materials - Equity - Beauty	2006	2016	**3 Typologies** - Renovation - Landscape or Infrastructure (non-conditioned development) - Building.	- Living - Petal

Table 4-17: Main Features of Various Building Environmental Assessment Tools

Furthermore, different structures and evaluation methods have been developed under these systems, and each scheme can have a long list of unique criteria beneath the overall structure. Thus, without knowing all the criteria within a certification scheme, as well as understanding how they are evaluated, it remains difficult to understand the value of the certification for specific building projects. In addition, it is difficult to understand how the qualities of a given certification system differ from other systems. The majority of these tools focus on environmental issues and do not consider economic or social sustainability. These tools are covering various aspects of sustainability and a number of credits and points are available under each category and the total of the credits or points are used to determine the overall performance of the building, thus the rating system differs from one project to another. Furthermore, materials and resources, energy, water, and indoor environmental quality are the most common aspects which have been noticed in the examined tools. Almost all the studied tools have energy as the main credit criterion

The number of environmental items is much larger with more detail than social and economic items. The energy category has the highest percentages in the all mentioned tools with a range between 20-35%, followed by the indoor environmental quality (16-20%), then the materials category in a range between (8-15%). Moreover, CASBEE assesses the environmental quality (Q) and environmental load reduction (L) of the buildings separately to ultimately evaluate the built environment efficiency, while LBC defines the most demanding standard and all imperatives are mandatory. LBC is based on the actual performance of the building rather than modelled or anticipated performance (the evaluation are normally carried after 1 year following the completion of the construction).

It should be noted that, the particular contributions of these tools to the 17 SDGs and their targets remained indistinguishable. This is mainly because these tools are evaluating the rate of the building's greenness using various indicators and categories, so a standard framework is required for uniformity.

4.2.2 Material-Related Items in the examined Building Environmental Assessment Tools

The material criteria were evaluated to identify the current features and weaknesses as balanced material assessments for materials selection. Generally, the material category of the six investigated tools is intended to reduce the environmental impacts throughout the building lifecycle, such as reducing the embodied energy and CO_2 emissions, improving resource efficiency, and minimizing waste. The findings of this chapter proved that all examined tools have materials category in common with sub-categories ranging from six to fifteen. The materials weights are 13%, 8-13%, 15%, 8% and 10-24% in BREEAM International NC, LEED, CASBEE, BEAM plus and GBCA Green Star, respectively. (LBC does not have credits or weights). See **Figure 4-7**

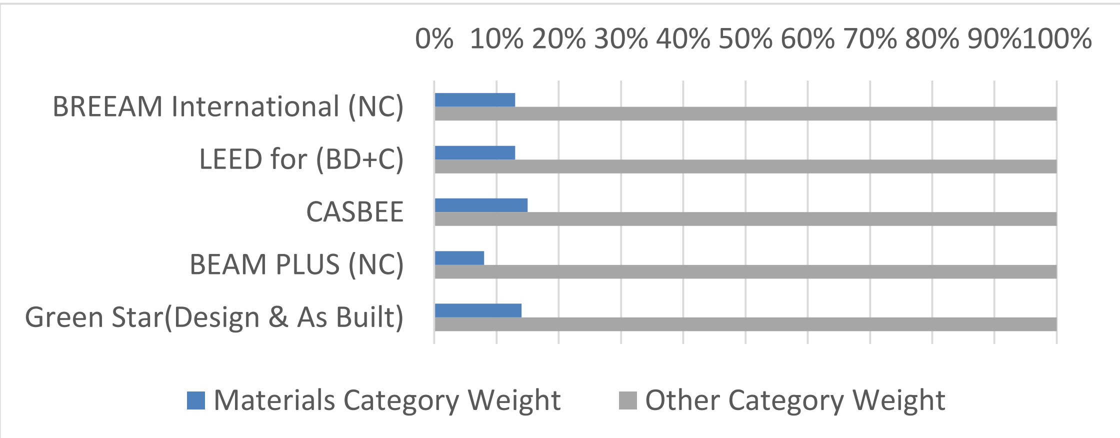


Figure 4-7: Quantitative Comparison of Materials Category Weight

All tools commonly show that the weight of “Material” is after those of energy, site, and indoor environment quality (IEQ). On the other hand, the material related items are not limited within the material category but are spread over a range of categories within the various tools such as energy, indoor air quality, etc. BEAM plus and CASBEE have the highest number of sub-criteria regarding the evaluation of materials. See **Figure 4-8**

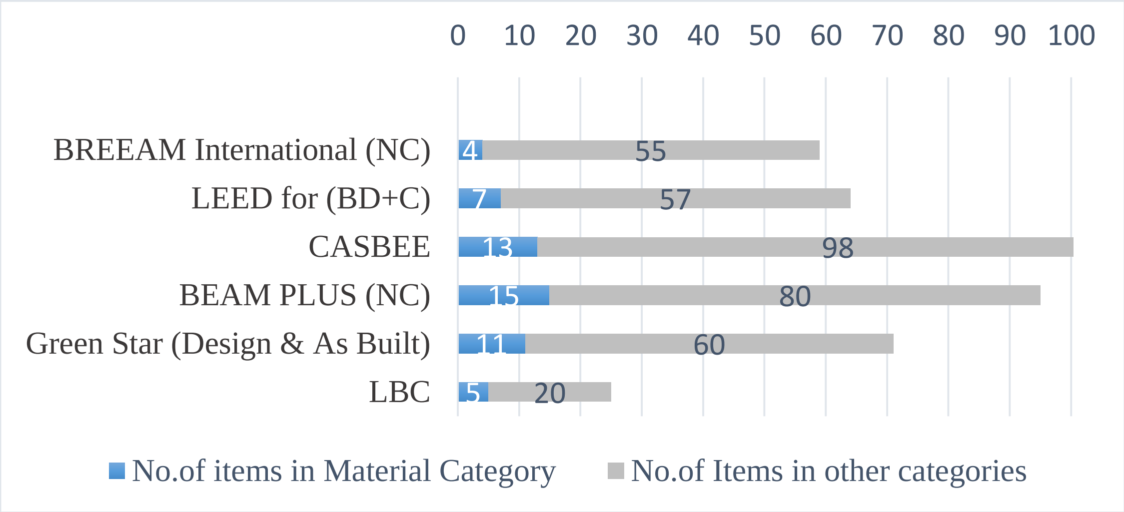


Figure 4-8: Quantitative Comparison of the number of items in the Materials Category

On the other hand, the responsible sourcing of materials and the building life cycle impact reduction have been noticed as common sub-items within the material category in the most investigated tools. For example, life cycle impact reduction has a significant share in the total materials credits (between 38-46%) which proved the significant impact of life cycle assessment on the evaluation of the environmental impact of products and materials. Nevertheless, BREEAM, LEED and Green Star assigned the highest credits and points for the life cycle impact reduction, while CASBEE and BEAM Plus focusing on reducing the use of materials by giving higher credits and weights to the reusability and recyclability of materials and components. Moreover, the materials category of the LBC is focusing on removing the worst offending materials and construction practices by creating a materials economy that is non-toxic, environmentally friendly, and socially equitable. See **Table 4-18**

To conclude this part, tools have been criticized for their poor adaptation, meaning none of these tools can individually perform a full study over the complete life cycle of building material. Comparative studies revealed that almost all building environmental assessment tools are limited geographically to regions where they are eagerly used (Goubran, 2019). Despite the above discussion, many improvements have been added to these tools to enlarge their scope and scale. However, the last versions of these tools need to be studied regularly in further depth.

Many intersections appeared amongst the examined environmental assessment tools in terms of the criteria they used to evaluate the environmental impacts of building materials. Thus, the integration of all three pillars of sustainability can provide a more balanced view of sustainability performance. However, the finding of this chapter proved that materials assessment is multi-dimensional and the need for creating a multi-criteria approach to aid decision-making in the selection of green building materials is essential. The process of creating a multicriteria framework for materials selection will be discussed in the following chapter.

Common Building Materials sub-category Credits	**Aims of the category/selection**	**BREE-M**	**LEED**	**CASBEE**	**Green Star**	**BEAM plus**	**LBC**
Life Cycle Impacts	Reductions in the building's environmental life cycle impacts through assessment of the main building elements	√	√		√		
Responsible Sourcing of Materials and Products	Key building materials are responsibly sourced to optimize the use of materials and to reduce environmental and socio-economic impacts.	√	√	√	√	√	√
Construction and Demolition waste reduction	Reducing the use of virgin materials to produce construction materials and cost reductions from waste disposal.		√		√	√	√
Materials without Harmful Substances or Ingredients (Red List)	Use of Materials without Harmful Substances/Pollutant Content		√	√		√	√

Table 4-18: Common Materials sub-category credits revealed in the investigated environmental assessment tools

CHAPTER 5: DEVELOPMENT OF A CONCEPTUAL FRAMEWORK FOR THE ASSESSMENT AND SELECTION OF BUILDING MATERIALS

5. CHAPTER FIVE: DEVELOPMENT OF A CONCEPTUAL FRAMEWORK FOR THE ASSESSMENT AND SELECTION OF BUILDING MATERIALS

5.1 Overview

The awareness of building stakeholders about the benefits of sustainable construction and green materials is increasing dramatically (J. Xu et al., 2020). Consequently, the demand for sustainable buildings becoming a rising trend that can be achieved by adopting sustainable concepts at early design stages. Hereof, building materials play a prominent role in determining the sustainability of a building throughout its life cycle, and making optimum decisions on the selection of building materials from the early stages of the building process is substantially valuable in terms of time, cost and resources. In assessing the suitability of building materials, more balanced decisions based on multiple criteria is needed.

The selection of materials is a crucial task in the architecture and construction field. It is the activity that designers and architects perform from the initial design stages until the final documentation stage (Fini & Akbarnezhad, 2019). A large number of materials are available today and they are bounded with a range of intrinsic and attributed properties and manufacturing constraints (See **Figure 5-1**). However, these issues are interconnected and should be considered holistically when making decisions. The significance of selecting a sustainable building material lies in the fact that an inappropriate selection could harmfully impact the occupant's health and comfort, the surrounding environment, and the whole life cycle cost of the building. Therefore, the question to be asked at this point is that ***what criteria, relevant respectively to the principles, have to be considered in the selection of building materials so that a confirmatory effect can be seen in buildings throughout their life span*?**

In real-life circumstances, the selection of building materials is commonly traditional based on the respective knowledge and experience of the stakeholders, which is most doubtful and ambiguous and often leads to poor decisions and further influences the building quality and client satisfaction. Material assessments are currently disregarded the modern development seen in material science, processing, and decision-making areas. Hence the initiation of a practical decision support framework for characterizing and managing uncertain information is essential. The successful implementation of material selection requires an input of a large amount of assessment data to promote multi-dimensional evaluation of criteria to aid decision-making. Nevertheless, the list of the assigned criteria should be satisfactorily accurate and inclusive to cover the broad range of issues that comprise the environmental, social, economic and technical values.

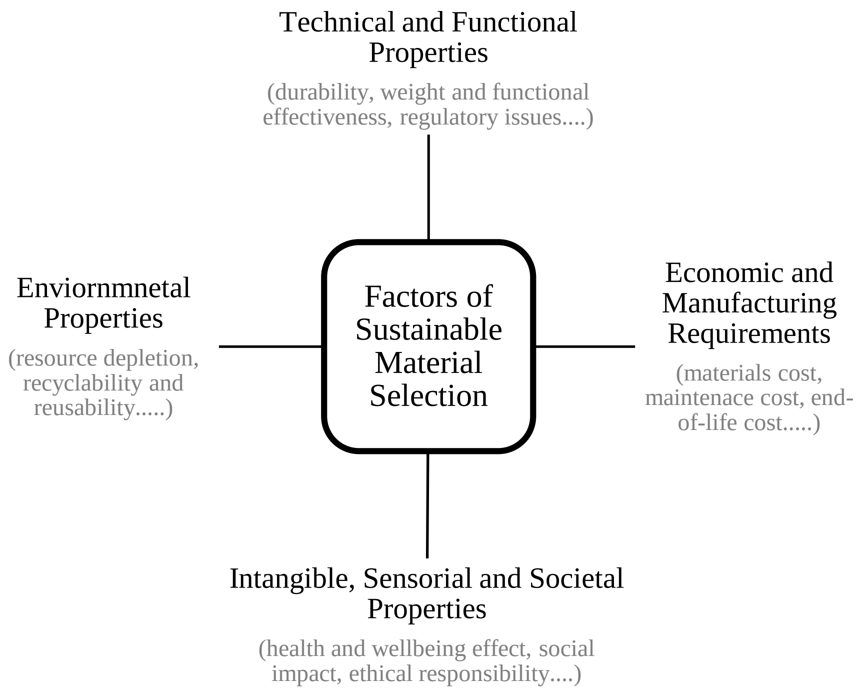


Figure 5-1: The necessary inputs for a holistic material selection process

5.2 Development of a conceptual framework for material selection

This framework aims to define evaluation criteria for the selection of green building materials based on scientifically recognized indicators and measures. Generally, material assessment and selection experience several distinctive, interdepended stages. The evaluation process cannot be seen as a simple direct process (linear) but follows a circuitous nature. Material selection is seen as an important multi-criteria decision making (MCDM) problem in engineering because of the requirement of considering multiple criteria from different dimensions. MCDM approach is consists of three major stages: research, evaluation, prioritization and selection of alternatives. However, this model is designed to create a sustainability index to quantitatively evaluate and rank material options for building projects at an early design stage.

The object of assessment is the non-structural façade and roof materials which could be integrated into building envelope assemblies. Generally, any individual material or composite material whether opaque or transparent, that is intended to be part of a wall/roof system or assembly could be targeted. The tool is designed mainly to be suitable for use in residential and office building types, nonetheless, it could be easily adapted to other types of buildings to move towards achieving sustainability in the construction industry. Furthermore, the model could be applicable for use in different countries with various climatic conditions since it included the most important criteria required for the assessment.

The research methodology applied for the proposed assessment framework is illustrated in **Figure 5-2**. Every stage can provide additional information contribute to the feedback loop to offer further information for a more detailed point for the forthcoming stages.

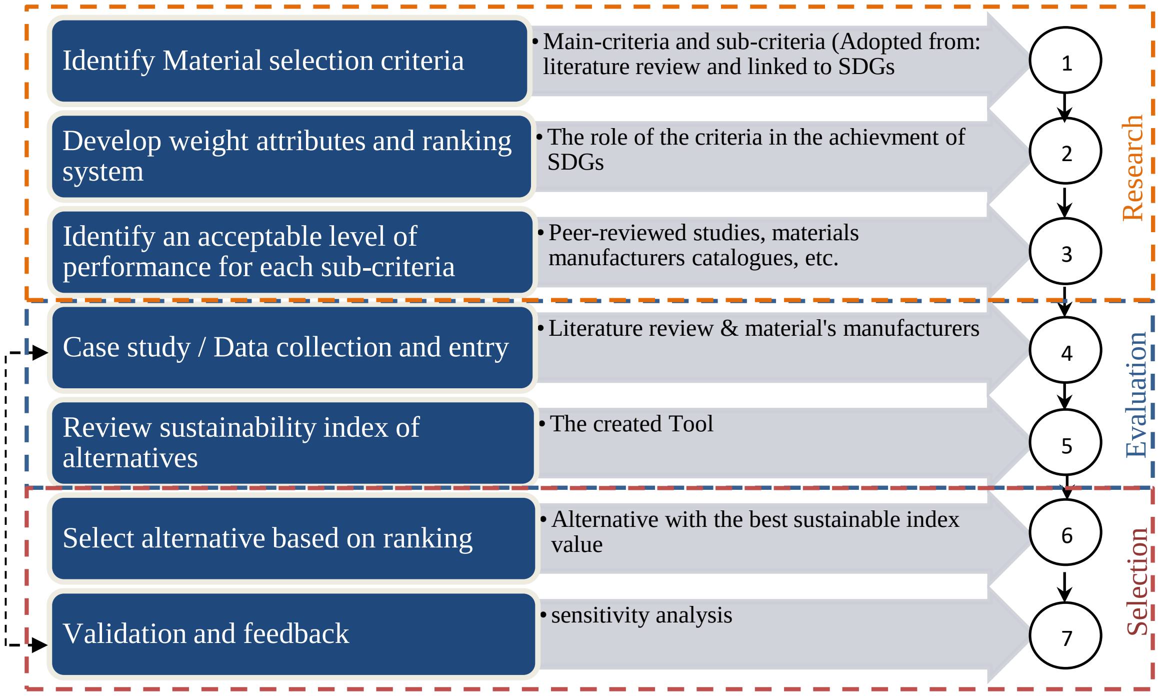


Figure 5-2: Stages to develop the assessment framework

During the research stage, the main-criteria and sub-criteria were identified in order to cover all aspects of sustainable development. Besides, the weight of the main-criteria was determined based on their role in the achievement of sustainable development goals and a point ranking system was developed to demonstrate the importance of the main-criteria and sub-criteria and to harmonize the units of each sub-criteria. Furthermore, a minimum acceptable range of the sub-criteria was identified to ensure that the least green-oriented requirements could be reached when selecting façade materials. The evaluation and selection stages were demonstrated by conducting several case studies and further information could be seen in chapter six. A detailed description of the research stage is provided in the following sub-sections.

5.2.1 Materials selection Criteria

The quality of the framework's outcomes largely relies on the selected criteria and the weighting assigned to it. Therefore the implementation of a logical method to identify the most appropriate criteria for a particular type of material is essential due to the importance of these parameters to project-specific location, stakeholder main concern, by-laws, as well as the environmental, economic and social status (Moussavi Nadoushani, Akbarnezhad, Ferre Jornet, & Xiao, 2017).

The comprehensive literature review demonstrated that no existing detailed list of assessment criteria that comprises the principles of sustainability, developed precisely for material selection in construction projects. Consequently, the following guidelines have been employed to select a set of inclusive criteria:

I. The criteria have been selected in a practical and transparent process to ensure that stakeholders could understand and identify them clearly and to cover all important characteristics of a decision problem.

II. The evaluation criteria items have been lessened as much as possible in order to lower the use of manpower, time and cost.

III. The criteria are intentionally selected to establish a clear vision for development that dedicates the same priority to the three pillars of sustainability (environmental, social and economic).

IV. The criteria that can be measured and evaluated have been chosen, to ease the comparison between alternatives.

The decision hierarchy for the selection of green building materials has been adapted from the literature review in the relevant field and from the examined environmental assessment tools. The literature review in chapter two and three have examined the important objectives of existing knowledge along with essential findings as well as a theoretical and methodological contribution to accelerate the research aim. Additionally, the proposed framework has been linked to the sustainable development goals of 2030 in order to nationalize the model and to select criteria that cover all aspects of sustainable development (See Appendix C-Table C1).

The new criteria are intended to increase the amount of information existing in the building material industry to support the selection of appropriate green building materials and assemblies and to achieve the UN sustainable development agenda (SDGs). See **Figure 5-3**

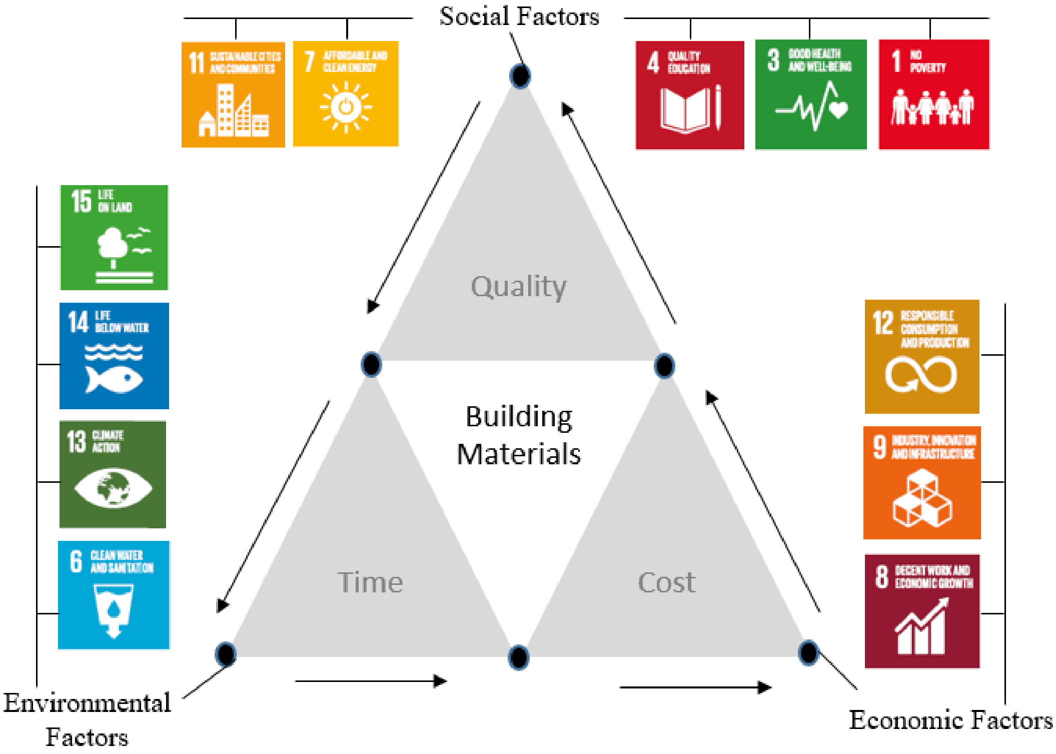


Figure 5-3: Green Building Materials Selection Triple Constraints

Furthermore, the new model seeks to broaden the focus of material selection by adding additional characteristics to the selection criteria. Therefore, the criteria have been classified into main and sub-category groups to cover the primary areas of selection when identifying materials as part of construction design. The main group include materials & resources efficiency, health and wellbeing, socio-economic performance, materials efficiency, water efficiency, and energy efficiency. The main five criteria have been formed through understanding the characteristics and specifications of green building material in alignment with the three pillars of sustainability (environmental, economic and social) and by extensively reviewing the material-related items examined in the most commonly used environmental assessment tools.

Then, each of the main criteria was assigned to several sub-criteria. These sub-criteria include all metrics that fall under the main factors, without which the achievement of the sustainable development goals would be impossible. The sub-criteria have been chosen to ensure that they have acceptable performance measures as well as they could be transferable and applicable among a range of alternatives irrespective of the local climatic conditions. **Table 5-1** shows the implemented criteria used in this study.

Main Criteria	Sub-criteria	ID	Implications	Reference(s)
Resource and material efficiency (RME)	Recycled content	RME1	The use of higher recycled content material can reduce the use of virgin materials and extraction of natural resources as well as minimizing solid waste disposal and make a substantial contribution to sustainable development.	(Ibrahim, 2016; WRAP, 2007)
	Reusability and Recyclability	RME2	In general, material reuse has the potential to reduce the embedded impacts, since reused materials often have low environmental footprints.	(Nußholz, Rasmussen, Whalen, & Plepys, 2019)
			The benefits of using recyclable materials are minimizing energy use, sustaining resources, reducing solid waste, and maximizing environmental benefits.	(Kubba, 2010)
	Durability	RME3	Durable materials that require less frequent replacement will require fewer raw materials and will produce less landfill waste over the building's lifetime.	(Peter O. Akadiri et al., 2012)
Socio-economic Performance (SEP)	Initial Cost	SEP1	Initial material cost represents the current market prices. It often guides decision making about what materials to choose.	(Illankoon & Lu, 2019)
	Maintenance Cost	SEP2	Maintenance cost has been considered a crucial part of the life cycle of a building.	(Flanagan & Jewell, 2008; Martínez Rocamora, Solís-Guzmán, & Marrero, 2017)
	Replacement Cost	SEP3	The replacement cost is the amount of money required to replace an existing material with the same quality at the present market price (generally: materials with a shorter lifespan need to be replaced eventually).	(Shadram & Mukkavaara, 2019)
	Demolition Cost	SEP4	This is an essential cost element of building life cycle cost (associated with the end of the lifetime of building materials).	(AbouHamad & Abu-Hamd, 2019)
	Locally Available	SEP5	The utilization of locally available materials in the construction industry generates several economic and sustainability advantages by reducing transportation costs and related energy and carbon emissions.	(Matalkah et al., 2017)
	Labour Availability	SEP6	Making use of the local labour force is seen as very essential to provide labour and social sustainability, aiming to reduce the percentages of unemployment and social exclusion.	(Castro-Lacouture et al., 2009)
Health and well-being impact (HW)	Red List	HW1	The concept of the red list is to avoid building materials and products that contain chemical substances and to choose products assessed uncritical for human health and the environment	(Ilvonen, 2013)
	Moisture Content	HW2	The control of moisture is important to protect occupants from adverse health effects associated with poor indoor air quality and to protect the buildings.	(Kreiger & Srubar, 2019)
	Fire Resistant	HW3	The application of fire-resistant materials in buildings is vital since they would indisputably contribute to a reduction of losses of life and human assets.	(Lahoti, Tan, & Yang, 2019)
	Embodied Carbon	HW4	Selecting low-carbon building materials is considered a key factor to mitigate carbon emissions in buildings.	(Pacheco-Torres, Jadraque, Roldán-Fontana, & Ordóñez, 2014)
	Visual Comfort	HW5	The finishing and colour of building materials are the most important factors that directly affect the quantity and the quality of light, and thus they have physiological and psychological effects on people who spend most of their time indoors.	(Cheong, Teo, Koh, Acharya, & Man Yu, 2020; Makaremi, Schiavoni, Pisello, Asdrubali, & Cotana, 2017)
	Acoustic comfort	HW6	The employment of sound-absorbing material is considered an effective way to mitigate noise-related health problems and improve the acoustic quality of the built environment.	(Bhingare, Prakash, & Jatti, 2019).
Water Efficiency (WE)	Embodied Water	WE1	The indirect water consumed during the construction process from the extraction, production, manufacturing, and delivery, is of great significance for water conservation.	(R. H. Crawford & Pullen, 2011)
Energy Efficiency (EE)	Embodied Energy	EE1	Using low-embodied energy material in construction can reduce the embodied carbon and energy consumption over a building's life-cycle.	(Dixit, 2019)
	Thermal conductivity	EE2	Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity.	(Khoukhi, 2018)
	Specific heat capacity	EE3	Specific heat capacity is an important criterion for building materials that are used for the thermal evaluation of building constructions.	(Pan, Zou, & Jin, 2017)
	Density	EE4	A high-density material maximizes the overall weight and is an aspect of low thermal diffusivity and high thermal mass.	(Mohammad & Shea, 2013)

Table 5-1: The main-criteria and sub-criteria of the decision model

The new framework is expecting to increase the research into sustainable and multipurpose materials where materials could be utilized for a variety of functions at the same time, such as durable, recyclable, energy-efficient, healthfully maintained and so on. such kind of materials can improve building sustainability from cradle-to-grave.

Figure 5-4 shows the main-criteria and sub-criteria of the decision model.

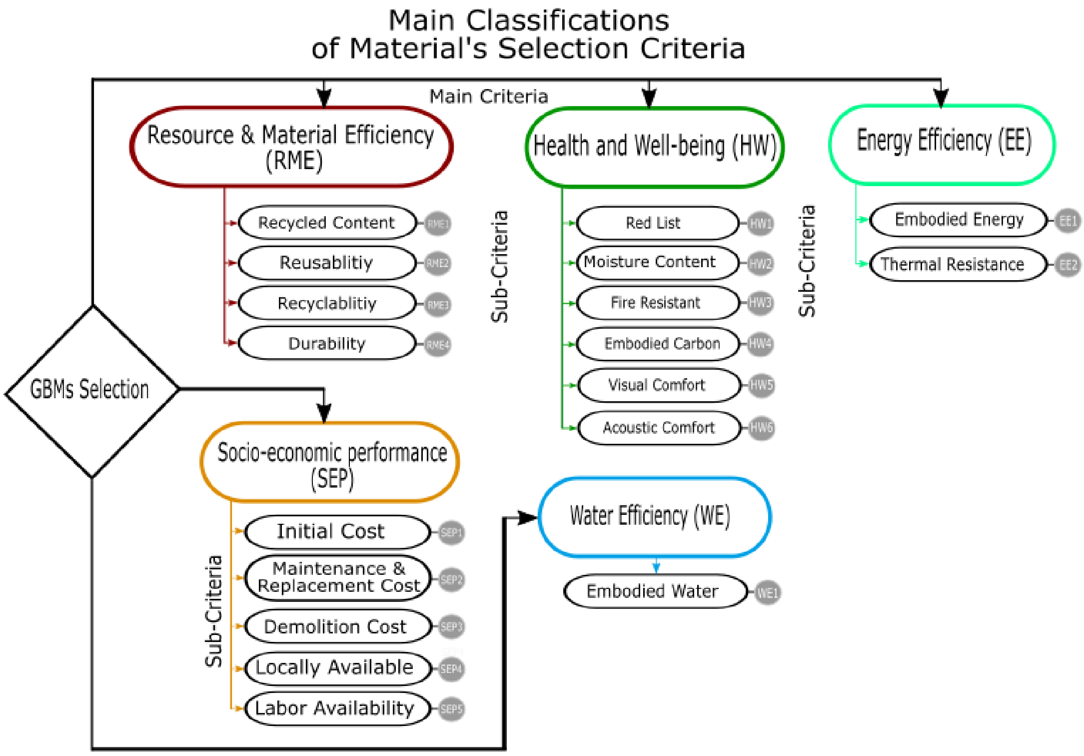


Figure 5-4: Green Building Materials Selection Criteria

In the past, basic methods examining a few criteria are often used in the decision-making process of materials selection which guiding to minimal solutions. One of the most optimal approaches to achieving green building is to select materials that reduce the environmental footprint. In this regard, the decision hierarchy for selecting green building materials started by dividing the model into four levels including the main objective (GBMs selection), sustainable development goals, main classification of materials criteria, and sub-criteria. See **Figure 5-5**

However, the approach of this model is to select the criteria for building materials that will help in the achievement of UN SDGs. Also, the criteria of the model have been linked and updated with the criteria identified from a comprehensive literature review and the examined environmental assessment tools in an attempt to create an inclusive judgment when dealing with material selection.

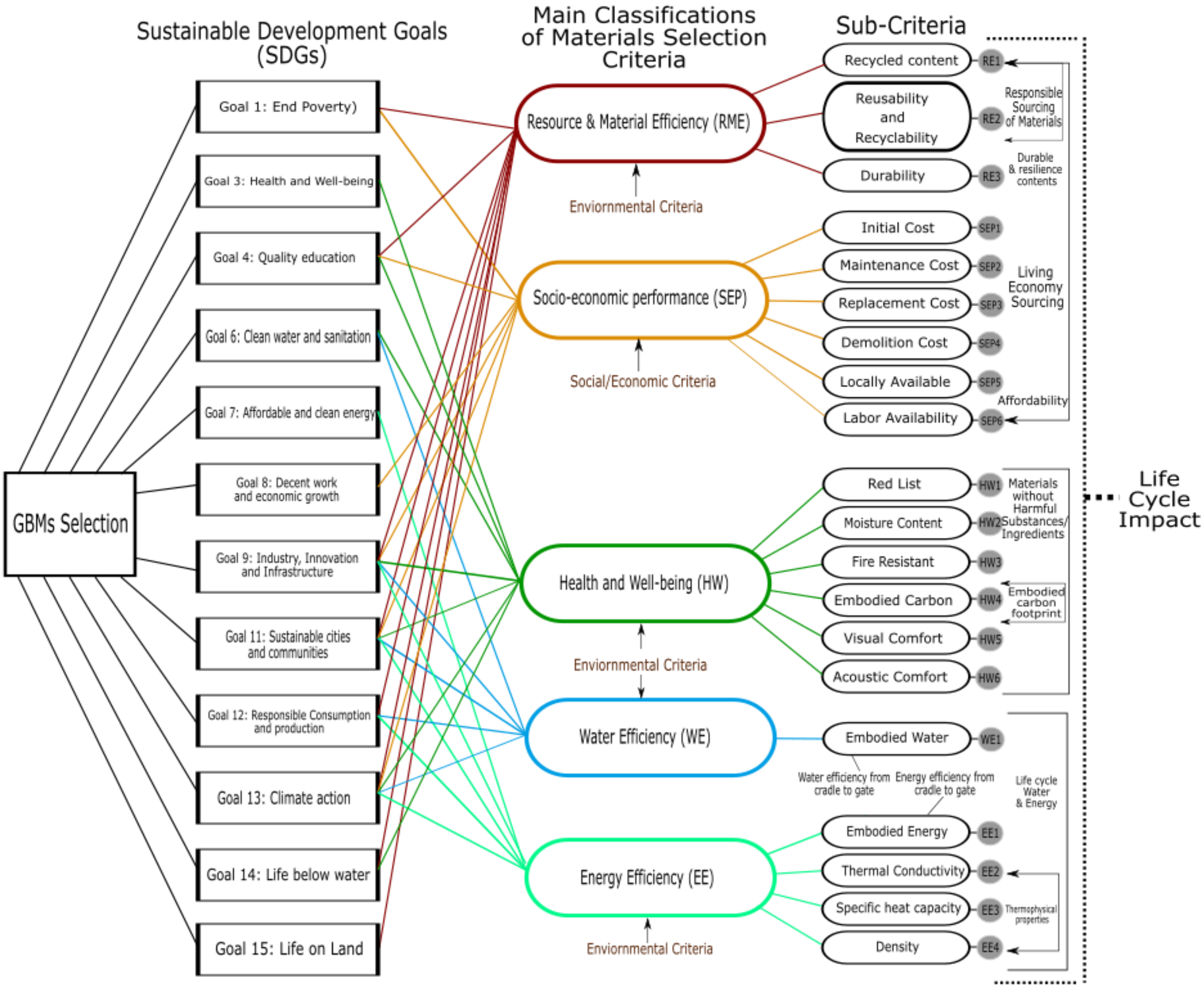


Figure 5-5: The Decision Hierarchy for Selecting Green Building Material

It should be noted that, although the criteria have been chosen to be applied internationally, the influence of the locality on their selection has been considered throughout the framework. The idea is to identify universal benchmark values for the implemented criteria that can improve the sustainability of building materials at the local level. In each local context, collecting the materials database can obtain a comparison between the local building materials to identify alternatives that can satisfy these global values. In fact, the value of each criterion should be obtained from the local building materials manufacturing database to make an effective analysis and to make transparency in the local construction market at a specific location. For instance, in the socio-economic performance index, the availability of local building materials and labours (local resources and knowledge) has been considered as the most important criteria to evaluate alternatives in this index to support the development of the local economy, meeting resource limitations, while finding solutions to societal challenges. Moreover, in the energy efficiency index, the thermal resistance performance of the building materials and their thermophysical properties have been counted in response to the climatic conditions and context. Likewise, the durability criteria (life expectancy of building materials including maintenance and replacement cycles) have been considered to be capable of adapting to the specific area and condition of use. Further explanations have been provided within each sub-criteria in the assessment and specification of the green building materials criteria section.

5.2.2 Weighting attributes and ranking system of materials selection criteria

Weighting is the numerical process that allows for the relative importance of a particular type or category to be transformed. It allows for assessing the decision-maker choices. In the construction industry, the difficulty of the weighting systems is still the main barrier to the acceptance of many evaluation tools and indexes (G. K. C. Ding, 2008). In general, selecting one material from a list of options means that materials must be ranked in each criterion to reflect its importance. While criteria may be calculated using different units, normalization is needed to transform these criteria into a standard platform to build a comparable index. Hence, this research part aims to create a ranking system for selecting building materials on a logical and practical basis. The system is intended for evaluating and choosing alternatives based on the values and not the preferences of the decision-makers.

First of all, the five main selection criteria have been ranked using a simple aggregation method. The weighting starts by assigning a constant weight to each sustainable development goal (8.3%); straightforwardly by considering that the twelve goals which building materials can achieve (Omer & Noguchi, 2020) are equal in weight. Secondly, the five main selection criteria are weighted based on their contribution to the achievement of SDGs. The weight has been obtained simply by multiplying the number of goals (SDGs) in which the five main criteria can achieve by the constant weight obtained earlier.

The total share of each main criteria has been estimated by the following equation:

$$S_c = \sum 8.3_{cw} \times N_{SDGs} \quad (5)$$

Where:

S_c is the total share of each main criteria in the achievement of sustainable development goals.

8.3_{cw} is a constant weight given to each sustainable development goal.

N_{SDGs} is the number of sustainable development goals which each of the main criteria could achieve.

The weight of each main criteria from the total share has been obtained by the following equation:

$$W_c = \frac{S_{C\,(RME,SEP,HW,WE,EE)}}{\sum(S_{C,RME} + S_{C,SEP} + S_{C,HW} + S_{C,WE} + S_{C,EE})} \quad \ldots\ldots(6)$$

Where: W_c is the weight of each main criteria in comparison to others.

$S_{C,RME}$ is the total share of resource and material efficiency criteria, $S_{C,SEP}$ is the total share of socio-economic performance criteria, $S_{C,HW}$ is the total share of health and wellbeing criteria, $S_{C,WE}$ is the total share of water efficiency criteria, $S_{C,EE}$ is the total share of energy efficiency criteria. **Figure 5-6** shows the weight of the main criteria based on their contribution to the achievement of SDGs.

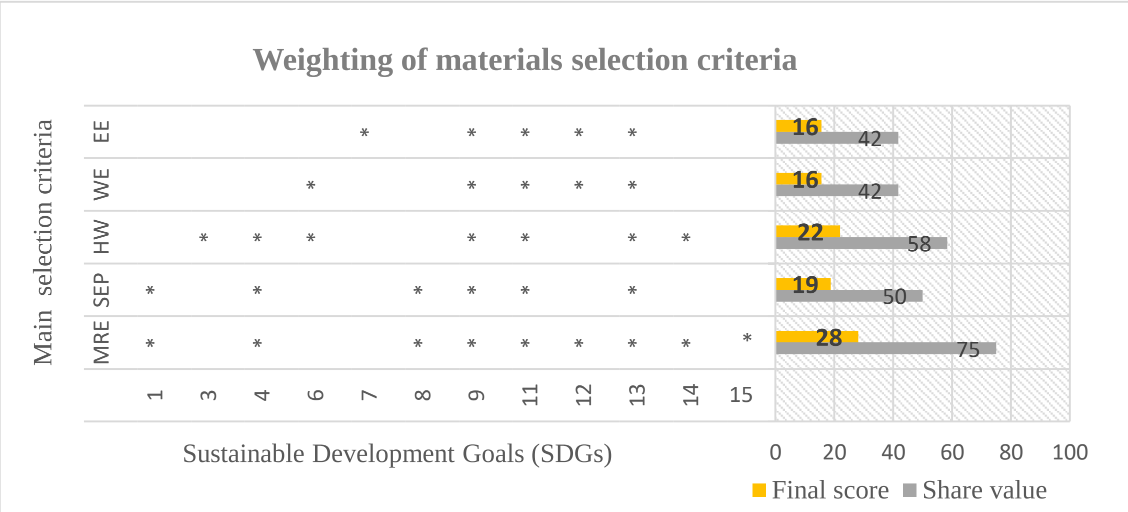


Figure 5-6: Rank of green building material criteria based on their contribution to the achievement of SDGs

Note: MRE=Material resource efficiency, SEP=Socio-economic performance, HW= Health and well-being, WE=Water efficiency, EE= Energy efficiency.

The next step is to determine how alternatives will be scored against the evaluation sub-criteria. A constructed scale based on a point system has been developed by the authors to evaluate building materials in each sub-criteria. The system is intended to support decision-makers and to make the material‘s selection process more explicit and transparent. Furthermore, the point system is very useful as it enables alike quantitative and qualitative criteria to be measured and compared as well as it has been realized to be more precise than human beings (experts) judgment. The method establishes a point system that ranges from 0 to 10 that can vary every 2 points, where 0 implying the worst level of performance and 10 the best level. Six rankings[21] are employed to determine the performance of building materials on all sub-criteria (**Table 5-2**). The point score is considered as an indication of how relatively the material value can achieve a certain sub-criteria.

Points		Definitions
u_i=	**0**	If a Material value is not effective to achieve sub-criteria
u_i=	**2**	If a Material value is weakly effective to achieve sub-criteria
u_i=	**4**	If a Material value is moderately effective to achieve sub-criteria
u_i=	**6**	If a Material value is strongly effective to achieve sub-criteria
u_i=	**8**	If a Material value is very strongly effective to achieve sub-criteria
u_i=	**10**	If a Material value is extremely effective to achieve sub-criteria

Table 5-2: A point scale for ranking building materials based on their ability to achieve the sub-criteria

The previous figure shows that material and resource efficiency criteria have the highest score among other criteria (28%), following by health and well-being (22%), then the socio-economic performance (19%). Furthermore, energy efficiency and water efficiency have the lowest share (16%) in achieving SDGs.

The sub-criteria categorized beneath the main criteria are assumed to have equal importance (weight) in the final index for each main criteria. Thus, the achieved points under each sub-criteria are summed and then the average points are used to show the final index for each main-criteria. The arithmetic mean formula is used for this calculation:

$$\overline{Sus_{index}} = \frac{\sum_{i=1}^{N} Sub_i}{N} = \frac{Sub_{c1}+Sub_{c2}+\cdots+Sub_{cn}}{N} \quad (7)$$

Where:

$\overline{Sus_{index}}$ is the sustainability index for each main criteria.

N is the total number of sub-criteria under each of the main-criteria; denoted as Sub_{c1}, Sub_{c2}… Sub_{cn}.

The final sustainability index is obtained by converting the points achieved under the main criteria into weights and then the sum of the weights is symbolizing the final index. The weight is calculated based on a factor that the higher the points the more likely is the material to achieve that criteria. In simple words, the weights are expected to reflect the

[21] Ranking scales with six or more response categories are generally more valid and consistent than those with three or five points.

importance of the material values in the index. The significance of the same points varies between indexes as a result of the difference in the weight of each main-criteria in achieving sustainable development goals. (See **Table 5-3**).

MREI		SEPI		HWI		WEI		EEI	
Points	Weight	Points	Weight	Points	Weight	Points	Weight	Points	Weight
10	0,28125	**10**	0,1875	**10**	0,2188	**10**	0,15625	**10**	0,15625
8	0,225	**8**	0,15	**8**	0,175	**8**	0,125	**8**	0,125
6	0,16875	**6**	0,1125	**6**	0,1313	**6**	0,09375	**6**	0,09375
4	0,1125	**4**	0,075	**4**	0,0875	**4**	0,0625	**4**	0,0625
2	0,05625	**2**	0,0375	**2**	0,0438	**2**	0,03125	**2**	0,03125

Table 5-3: The weight of the points in several criteria indexes

Note: MREI=Material resource efficiency index, SEPI=Socio-economic performance index, HWI= Health and well-being index, WEI=Water efficiency index, EEI= Energy efficiency index.

For instance, if material scores 10 points under the resource and material efficiency that indicates the material has the opportunity to completely achieve the criteria and thus the previously obtained weight of the criteria (28%) will be assigned to that material. In contrast, achieving 2 points under the same criteria signifies that the material could achieve 20% of the total criteria weight (5.6%). The weights and the final index are represented in a decimal form to make it easier to control mathematically. This method yielding a single index allowing material alternatives to be ranked. The following equation is used to calculate the final index:

$$Sus_{final} = \sum_{i=1}^{5} Sus_{index} = Sus_{index1} + Sus_{index2} + Sus_{index3} + Sus_{index4} + Sus_{index5} \quad (8)$$

Where:

Sus_{final} is the final sustainability index.

Sus_{index1} is the resource and material efficiency index; Sus_{index2} is the socio-economic performance index; Sus_{index3} is the health and wellbeing index; Sus_{index4} is the water efficiency index; Sus_{index5} is the energy efficiency index.

After all, the best material is selected based on its final index weight. The material with the highest sustainability index is expected to have a significant role in achieving main-criteria and sustainable development goals more than other options.

The detail of the assessment method and the sustainability index of each sub-criteria will be discussed in the following Section. The section will focus on the definitions of each sub-criteria as well as the way that it is going to be evaluated

5.3 Assessment and specification of green building materials criteria

5.3.1 Resource and Material Efficiency (RME)

Resource efficiency is a concern of using the earth's natural resources sustainably while minimizing their environmental impacts. Material resource efficiency can be applied throughout the building's lifetime, from the extraction of raw materials for use in the construction stage, through operation use and maintenance, to material recycling at the demolition phase. The sustainability of building materials is depending on using a circular loop system (Use-collect-process-reuse) rather than a liner loop system (extract-manufacture-use-discard) (W. Mark & Kestner, 2010). The three R's of waste management comprise reduce, reuse and recycle; helping to conserve natural resources, landfill space, energy, as well as cutting down the amount of construction waste (See **Figure 5-7).**

Figure 5-7: Circular Loop of Sustainable Building Materials

In the construction industry, the extraction and the consumption of natural resources for the production of building materials has a direct impact on the built environment. The construction and buildings are responsible for 40% of global resource use (United Nations Environment Programme, 2014). In particular, a large amount of non-renewable resources are consumed in the built environment. Therefore, the need for a practical and consistent information to inform decision-makers regarding resource-efficient building materials is highly needed. The optimization of resource usage and the minimization of the waste generation of building materials could be enabled through using higher recycled contents materials, reusing and recycling construction waste, and using durable materials. However, a set of clearly defined and measurable criteria and indicators should be considered when selecting materials at the project initiatives and design phases.

5.3.1.1 Recycled content:

ISO 14021 (1999) defines recycled content as " *the proportion, by mass, of recycled material in a product or packaging*" by considering pre-consumer and post-consumer materials. The pre-consumer material can be defined as a material generated from the waste flow during a manufacturing process, they are being referred to as pre-consumer recycled content (sometimes referred to as post-industrial), wheat straw, sawdust and fly ash are examples.

The post-consumer materials are " *materials generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product, which can no longer be used for its intended purpose*", for example, plastic, paper, glass and metal. The use of post-consumer content will prevent materials from ending up as solid waste in the landfill which effectively turn waste into useful resources[22]. However, the selection of building material with a higher recycled content will help in reducing the use of virgin materials and extraction of natural resources as well as minimizing solid waste disposal (Ibrahim, 2016). See **Figure 5-8**

For each material, the percentage of recycled content is the sum of the per cent of post-consumer plus the per cent of pre-consumer. The percentages are based on weight, as follows:

$$\%\ \text{Post} - \text{consumer Recycled Content} = \frac{\text{wt.of post}-\text{consumer recycled content}}{\text{total material weight}} \ \ldots\ldots\ (9)$$

$$\%\ \text{Pre} - \text{consumer Recycled Content} = \frac{\text{wt.of pre}-\text{consumer recycled content}}{\text{total material weight}} \ \ldots\ldots\ (10)$$

$$\text{Percentage Recycled Content} = \%\ \text{post consumer recycled content} + \%\ \text{pre consumer recycled content} \ \ldots\ldots\ (11)$$

[22] The environmental risks are higher with post-consumer waste because if not recycled, the possibilities that it would end up as a landfill are greater than pre-consumer waste.

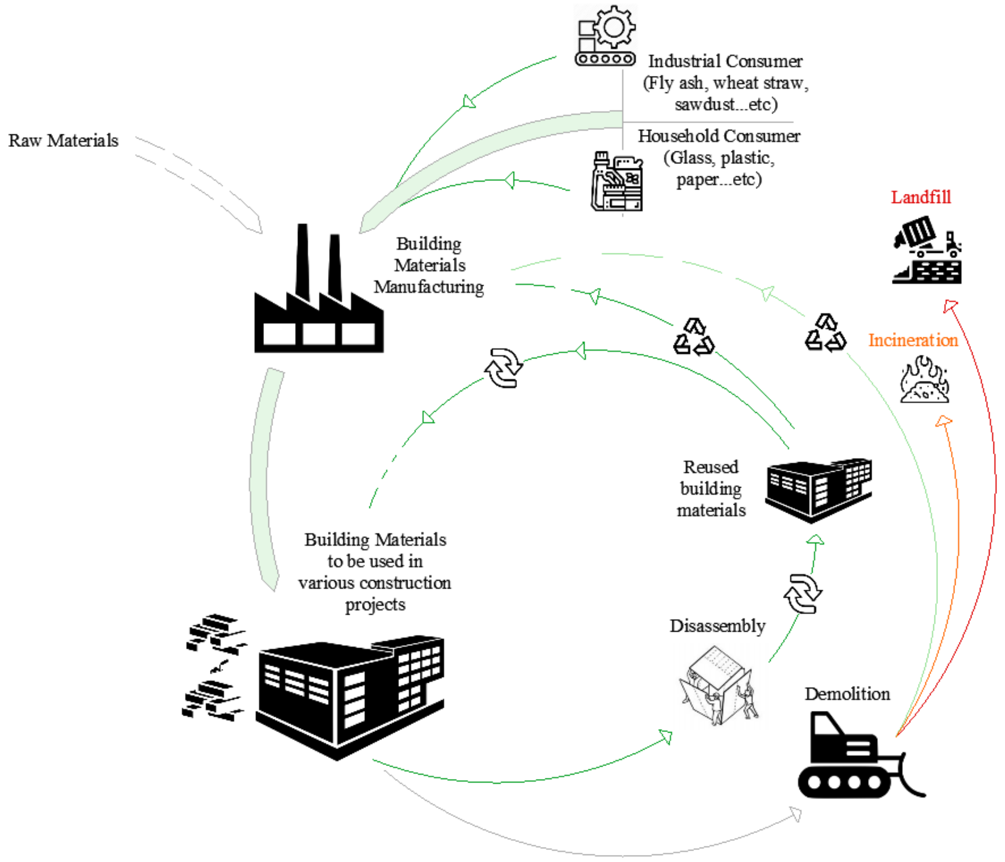


Figure 5-8: The principle of recycled content to close the material's loop cycle

On the other hand, some of the environmental assessment tools offer credit for recycled-content materials, for example, LEED rates the post-consumer content of the materials twice as much as pre-consumer content (See Appendix B-Table B2). It evaluates the use of materials with recycled content, so the total of post-consumer and pre-consumer recycled content represents 10-20% of the total material's mass (based on material's cost). Also, an additional innovative point can be achieved if the recycled content of the project reaches 30% or more. Furthermore, many public bodies in several countries have already established rules that require a certain percentage of recycled content to be included in the new products and packaging including construction products. For instance, The Federal Trade Commission of the USA (2012) set a minimum of 10% recycled content for glass products, fibreglass, tiles, construction blocks and flat glass sheet. Besides, the government-commissioned Sustainable Buildings Task Group of the UK proposed a baseline requirement for a minimum of 10% of reused/reclaimed or recycled content (by material value) in building projects (Emery, Smith, Gaterell, Sammons, & Moon, 2007).

One of the major barriers to manufacture products with higher recycled content is the concern of low quality (service life), cost, and performance (other properties) of the new products (see **Figure 5-9**). Nevertheless, with the development of advanced technology in the construction industry, it becomes possible to produce high-quality recycled-content products that meet or even exceed the performance of virgin products with a competitive cost. Yet, mandating a minimum percentage of recycled content by governments (standards and specifications) is the direct path to increase the demand for remanufacturing of recycled products and advance recyclables.

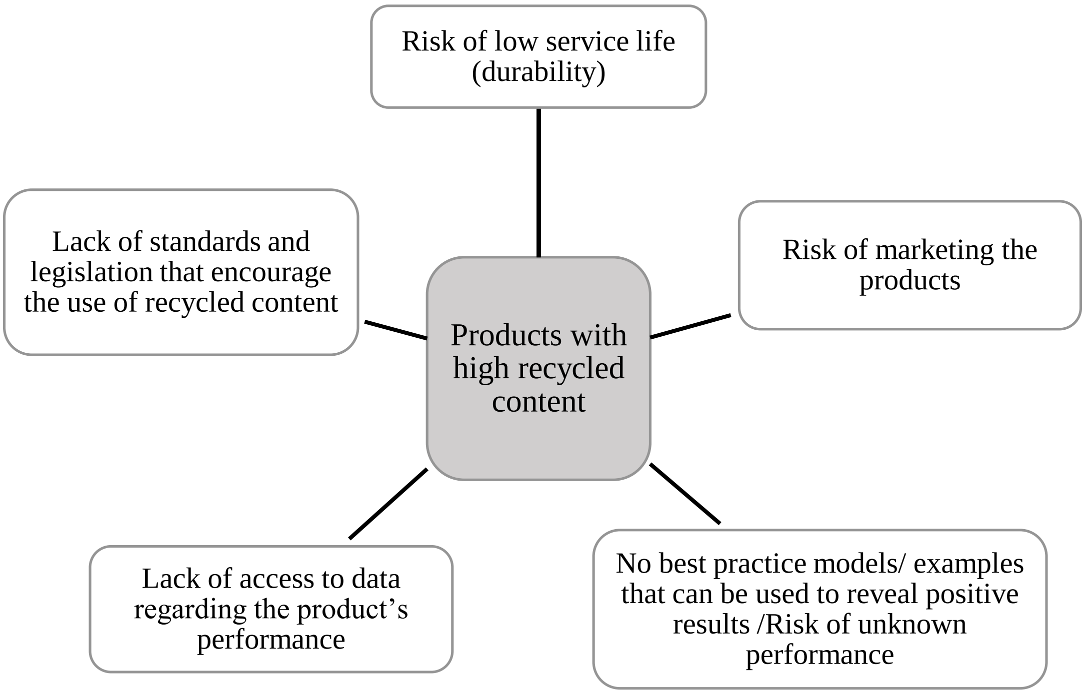


Figure 5-9: Key barriers to the perception of manufacturing and using products with recycled content

In this research, to compare alternative building materials in terms of recycled content[23], a point system is suggested to evaluate the weight of recycling and waste for each material. In the proposed model, 10 points will be assigned to the material with 100% recycled contents of its total weight, while 2 points will be given to the materials with low recycled contents (≥10% and <25% of its total weight). Furthermore, if the percentage of the recycled content of a given material is below 10% of its total weight, then no points will be given to that material. See **Table 5-4**

[23] When the recycled content information of building material is missing, it shall be assumed as virgin material. There is no obligation to collect all information, however only documented verifiable pre-consumer material and post-consumer material input shall be accounted as recycled content.

Percentage recycled content of Building Materials (RC material mass)	Points	Examples
100%	10	Terrazzo
≥75% and <100%	8	Cellulose Insulation
≥50% and >75%	6	Precast concrete blocks (made using Recycled Concrete Aggregate)
≥25% and <50%	4	Gypsum Plasterboard
≥10% and <25%	2	Ceramic Tiles
<10%	0	Rockwool

Table 5-4: Percentage of recycled content of some building materials

5.3.1.2 Reusability and Recyclability:

All building materials have a specific lifespan. Accordingly, there are four available options when a building material reaches the end of its lifetime including reuse, recycle, incinerate and landfill. The landfill and incinerate are the worst options because a large amount of material's embodied energy is not utilized besides the potential of polluting the environment by generating gases and toxic wastes. Reusability and recyclability, on the other hand, are the main sustainable approaches that can be used to minimize landfill waste, decrease the need for virgin materials and energy, diminish environmental consequences and pollution (air and water) associated with the building materials at the end of their lifetime. These two concepts are growing significantly as the environmental concerns are intensifying and the space for landfilling is becoming limited all over the world. They play a crucial role in shifting the building materials from a linear fashion into a circular economy approach (Minunno, O'Grady, Morrison, & Gruner, 2020). Up to date, recycling is considered the most applied approach in construction practices (Kirchherr, Reike, & Hekkert, 2017).

According to Gao, Ariyama, Ojima, and Meier (2001), the recycled building material is "a material, which can be remade and reused as a building material after the building is disassembled". Hence, recycling requires collecting, separating, processing and manufacturing. Furthermore, Thormark (2006) defines the recycled materials as products that shall not be subject to an extraction process, have a lower embodied energy than non-recycled ones, and could be recycled after demolition, while reused materials as products that can be used for about the same purpose as primarily intended. Moreover, Kovacic, and Rechberger (2019) stated four parameters that influence the recyclability of materials and building components including the mass, separability, accessibility, and lifespan.

According to Densley Tingley, Cooper, and Cullen (2017), reuse could be defined as the following use of an object after its first life in which the object might be reutilized while keeping its original form with minor changes. The reuse process needs less amount of energy and minimum waste to convert the material to operate its new function with equal performance in relation to the other processes (Vefago & Avellaneda, 2013).

Also from a socio-economic viewpoint, the reusing approach helps people to find materials at an affordable price while support construction stakeholders to move towards sustainable consumption alternatives. Examples of reuse involve the direct reuse of materials on-site extracted from a demolition or deconstruction project, or reusing remains materials for an under-construction or future project at another site. In a circular economy, the reuse of building elements in several life cycles aims at increasing resource efficiency and reducing waste (Cruz Rios, Grau, & Chong, 2019).

As stated previously, products that are recycled are created from materials that previously formed another object while recyclable means that the material can be reused when reaching its lifetime (recyclable materials do not necessarily contain recycled materials). However, it's very important to investigate the recycled content and the recyclability of the building materials individually, as it is not necessary for the product derived from recycled materials to be recyclable. Therefore, the most sustainable options for selecting building materials are those that are both recycled and recyclable.

Moreover, some researchers have focused on increasing the recycling potential of construction materials, for example, Verfago and Avellaneda (2013) classified the recycled materials that reached their end life stage as recycled, infracycled, reused or infraused and proposed a recyclability index which can be applied in the building design or at the end of the building lifetime. Ng and Chau (2015) calculated the embodied energy associated with different waste management strategies for a high rise concrete commercial building. The conclusion of their research revealed that recycling was the best option to have the highest energy-saving potential following by reusing and incineration.

Furthermore, Gao et al. (2001) examined the amount of energy and resources from the use of recycled materials in three types of residential buildings in Japan. The results showed that the energy consumption of remake housing materials from recycled materials is lower than the energy consumption to make new housing materials.

The method proposed in this part is intended to improve the decision making at the beginning stages of building design regarding the selection of building materials based on recyclability and reusability criteria. The early design stages play a crucial role in determining the future potentiality of buildings and materials to be reused or recycled as at this phase the judgments on materials arrangement will be encountered. The hierarchy of the new system is adapted from the existing literature knowledge based on three factors: energy saving, waste-minimizing and pollution reduction. See **Figure 5-10**

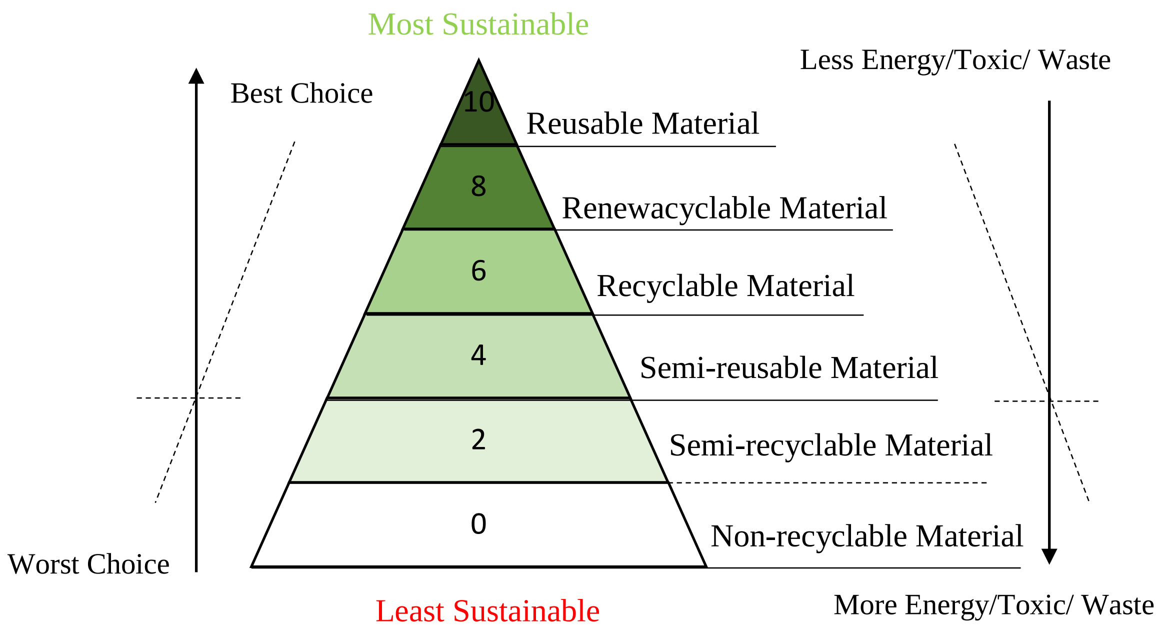


Figure 5-10: The qualitative hierarchy model for selecting building materials based on recyclability and reusability concepts.

Furthermore, a qualitative point system is proposed to distinguish between different building materials in terms of their recyclability and reusability index. However, the system composes of 10 points, in which the selection of reusable material is assumed to have the highest points (10 points) while the selection of recyclable material supposed to have 6 points. Furthermore, the renewacyclable material is a new concept that appeared in this part to define a new material that is renewable[24] in its source and can be recycled. This new concept will open the opportunities for using alternative materials that can be recycled multiple times and can provide sustainable living without harming the environment.

[24] A product can be considered renewable if its use life is longer that the time it takes to renew the material. For instance, redwood lumber can be considered a renewable product if it is in use for over 25 years.

In this research, the materials have been classified into six groups (at the end of their lifetime) and their definitions are summarized in **Table 5-5**.

Recyclability and reusability terms	**Definitions**	**Example (s)**
Reusable Material	A material that shouldn't have to pass through any kind of chemical or physical changes. It maintains its original properties and it doesn't necessary to be used for the same function in the next project.	A wooden beam/ Metal Beam
Renewacyclable material (Renewable Recyclable)	Material from a renewable source can pass through chemical or physical changes and doesn't require to maintain its original properties or any biodegradable materials which can return to the biological cycle after the end of its lifetime without contaminating the environment.	Plastics from cellulosic materials
Recyclable Material	A material that can pass through chemical or physical changes while it maintains its original properties and it doesn't necessary to be used for the same function in the next project.	Metal
Semi-reusable Material	A material that shouldn't have to pass through any kind of chemical or physical changes. It decreases its original properties and will be used for a different function in the next project.	Crushed ceramic brick/ Concrete blocks
Semi-recyclable Material	A material that can pass through chemical or physical changes while it decreases its original properties and it doesn't necessary to be used for the same function in the next project.	Plastics derived from petroleum
Non-recyclable or Non-renewable Material	A material that is not possible to reuse or recycle at the end of its lifetime.	Mortar and Cement

Table 5-5: The definitions of recyclability and reusability terms

It is expected that the amount of energy, waste and virgin resources will be minimized by selecting reusable materials during the early stage design decisions (Nußholz, Nygaard Rasmussen, et al., 2019). Following reusable materials, the preferred choice is to select renewacyclable materials by encouraging the use of renewable products which have endless recycling times. Furthermore, the semi-reusable and semi-recyclable materials have been replaced at the bottom of the hierarchy, being the last two options for selecting building materials. The application of semi-reusable building materials will help in reducing the amount of energy and virgin materials in the building more than in the case of semi-recyclable materials. See **Figure 5-11**

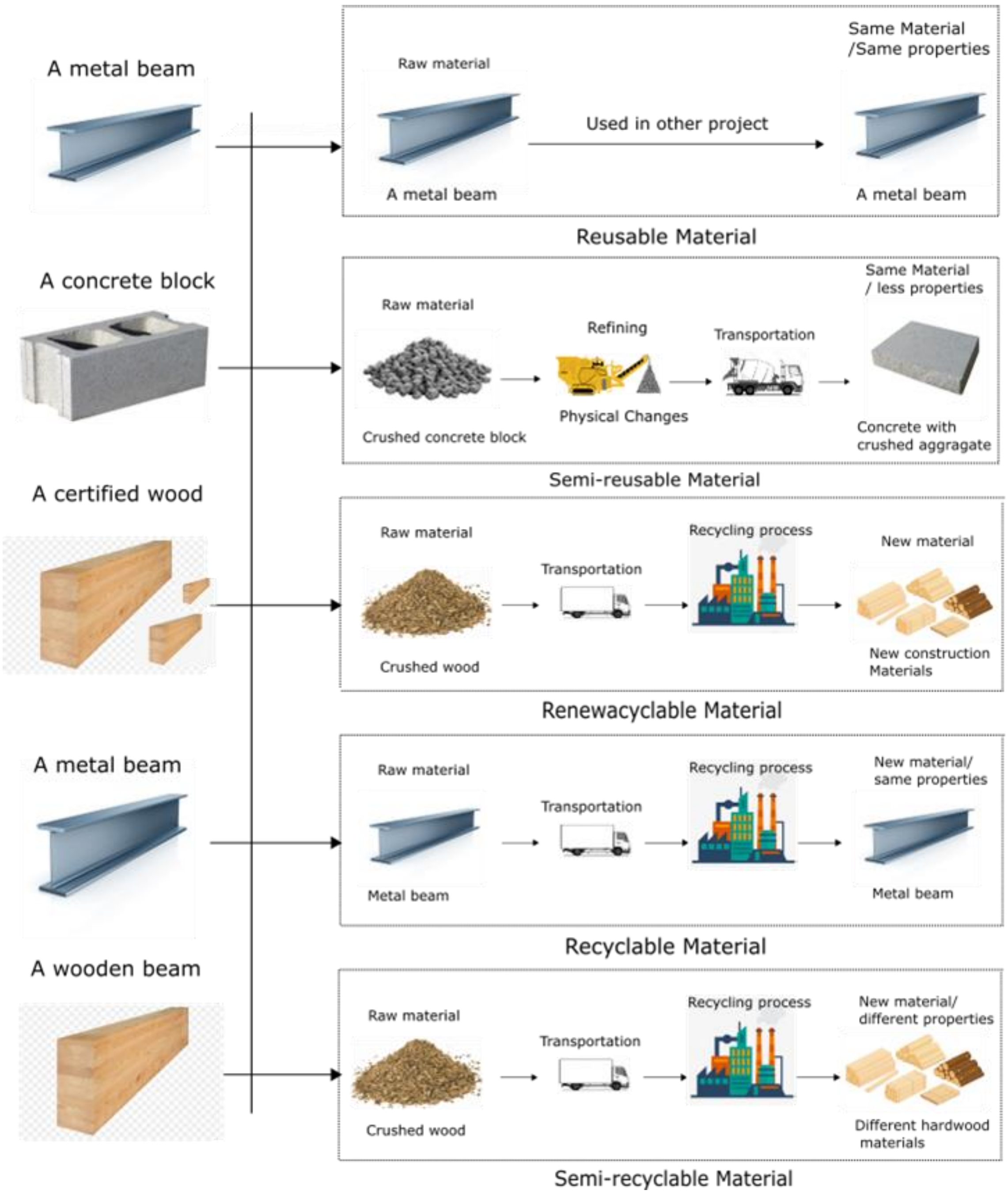


Figure 5-11: Possible options for selecting building materials and products based on reusability and recyclability approaches

However, materials like wood and steel can be considered reusable or recyclable products depends on their use after the demolition of the building. For instance, a metal beam from a demolished building can be used again like a beam in a new building (reusable product) or it can be recycled as a raw material to produce new products (recyclable products). Additionally, the use of natural materials can help in reducing the environmental impact associated with material's extraction and processing, thus natural materials are lower in embodied energy and toxicity than artificial materials (Godfaird John, Clements-Croome,

& Jeronimidis, 2005). However, in this part, natural materials have been classed under two categories depends on their sources, in the role of renewable natural materials and non-renewable natural materials. Renewable natural materials can be reused or recycled, thus can be classified either as reusable or renewacyclable materials, while non-renewable natural materials can be considered under each of the six mentioned categories depends on the applied method at the end of their lifetime.

5.3.1.3 Durability

Today's building practice has led to many failures and lack of durability, which can results in serious adverse consequences to the occupant's safety and comfort, building value, operation costs, functional drawbacks, and environmental impacts. The durability of building material can be defined as the capability of a material or a system to perform its desired functions during a specific time under defined outdoor and indoor climatic conditions and the construction of the assembly. The American Concrete Institute (ACI) (2013) defines durability as "the ability of a material to resist weathering action, chemical attack, abrasion and other conditions of service". It represents the ability of the material to resist degradation over its life cycle.

Durability is concerned with material performance or deterioration over the service life of the structure in a particular environment and is not an intrinsic material property. For instance, material that is durable in one environment may not be durable in another (Alexander & Beushausen, 2019). Moreover, the prediction of material's service life is based on verifiable data such as material properties, surface treatment, and geometric design but must also rest on assumptions of other data such as deterioration level and environmental exposure. In general, the field of application and the type of risks are two crucial factors to determine materials durability (Marteinsson, 2005). Therefore, the most practical method for evaluating the durability of building material is to confirm its functioning in similar applications where it has been subjected to real-life environments. See **Figure 5-12**

According to Lassandro (2003), it is necessary to change our thinking from single-use products to multi-use materials and components, considering the useful life of a building or apart. At present, the relationship between the material's durability and sustainability is oversimplified. However, building materials should be evaluated as a part of a multifaceted system, and their performances and durability have to be examined over the building's lifetime.

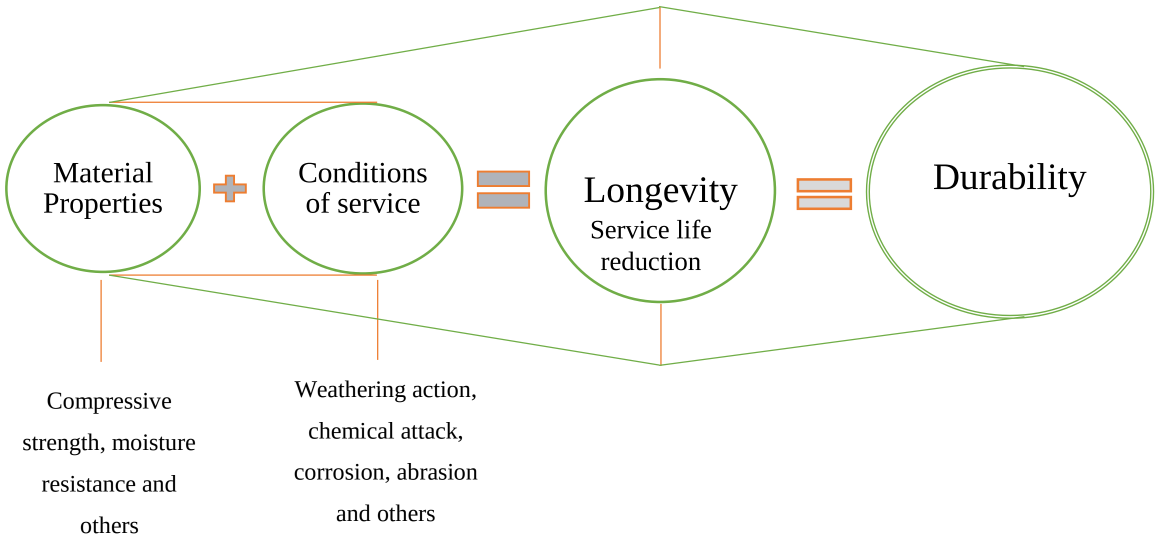


Figure 5-12: Parameters necessary for service life prediction

Furthermore, the environmental impact, energy consumption, raw material use and waste, and economic costs associated with the replacement and repairing of building materials and components will be minimized by selecting materials that will last for a long time. The longer a building material stays in operation, the lesser the embodied impacts are per year of service (W. Mark & Kestner, 2010). More and more often, it is acknowledged that the sustainability of buildings is a function of their durability. Therefore, selecting durable building material is a key factor for expanding material optimization in green buildings.

The building codes set minimum required levels of durability for different building elements. The service life of buildings and materials varies considerably around the world, but it is commonly believed that the estimated longevity of the building and its components should be as long as 50-60 years (Celadyn, 2014). For example, the New Zealand building code determined the durability requirements of the building elements to be 50, 15 or 5 years based on three main considerations. These were: ease of access, ease of replacement and detection of failure (Benge, 2001). According to Wong, Perera, and Eames (2010), the common life expectancy of a building elements varies from 5 to 60 years determined by the types and nature of the elements. The durability of the material depends on initial properties and the rate of decay in a specific service environment. Materials during the expected lifespan can be considered free of maintenance. Conversely, as a result of maintenance, the performance level of the material will differ from the first one. Thus, the service life of a specific material can be determined by both durability and maintenance (Chown & Oleszkiewicz, 1997) as shown in **Figure 5-13**.

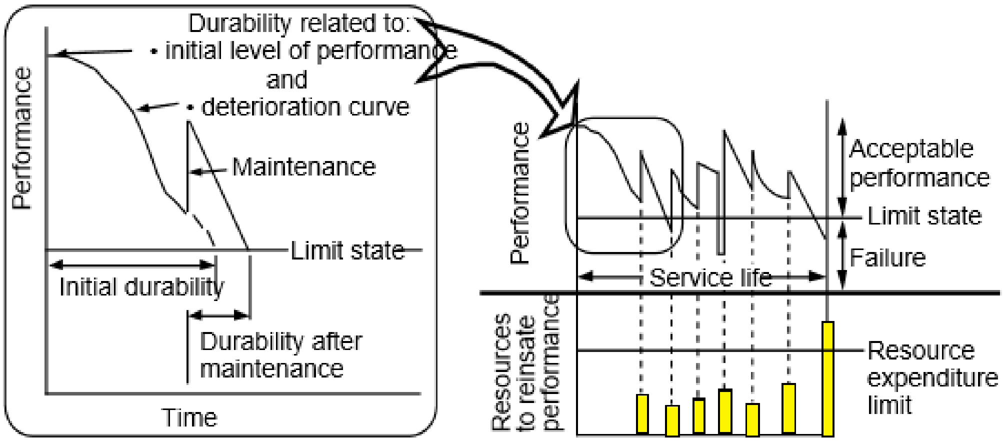


Figure 5-13: Durability, deterioration and service life

Adapted from (Chown & Oleszkiewicz, 1997)

On the other hand, several environmental and chemical factors affect the durability of the material during its service life. The environmental factors are the most significant factors like moisture content, temperature and exposure time.

Furthermore, the selection of durable building materials is linked directly by their intended function, for instance, the selection of long lifespan materials is highly required if the material is going to be used as part of the main structural system of the building or if it's difficult to be accessed for maintenance or replacement, while the selection of short lifespan material is allowed if the material is not used as a structural element and it has easy access for maintenance and replacement. See **Figure 5-14**

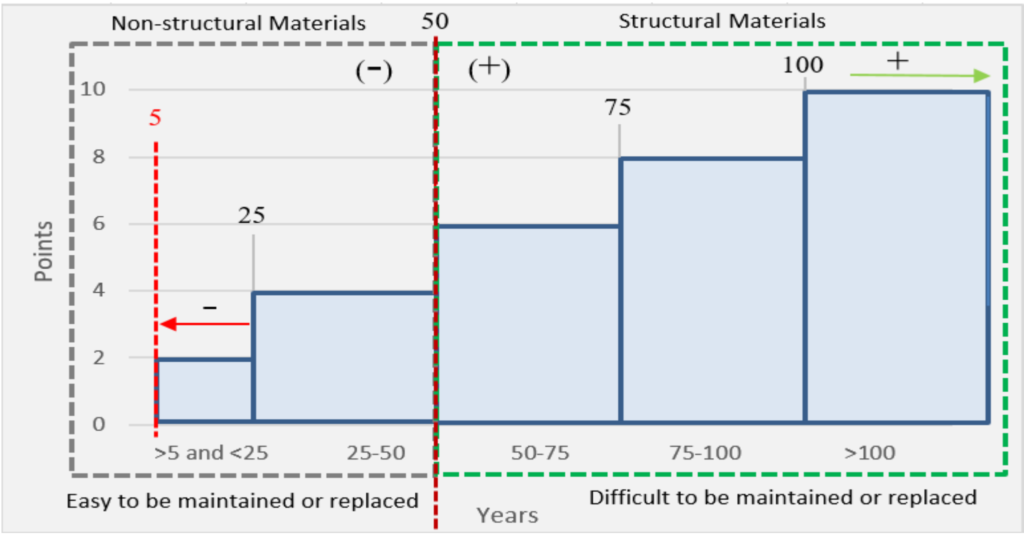


Figure 5-14: A rating system showing the required durability of building materials based on their intended function

In reality, the actual lifespan of the material is often much less than the predicted lifespan. In this research, a rating system based on the existing knowledge concerning the expected service life of building materials has been proposed. Higher points have been assigned to the building materials with an expected longer lifespan. The proposed model is intended to aid the selection of the most durable and sustainable materials among alternatives (See **Table 5-6).**

The life expectancy of building materials	Points	Examples
> 100 and lifetime	10	Natural stone
≥75 and <100	8	Concrete
≥50 and <75	6	Gypsum
≥25 and <50	4	Wood panelling
≥5 and <25	2	Interior paint
<5	0	Exterior paint

Table 5-6: The life expectancy of building materials and the assigned points

In conclusion, materials efficiency can be achieved by using higher recycled content and longer lifespan building materials, and by applying the reusability and recyclability approaches (**Figure 5-15**). The material resource efficiency index can be obtained by summing the points achieved under the above-mentioned categories as follows:

$$RMEI = \Sigma\ RCI + RRI + DI \quad \text{.......(12)}$$

Where: ***RMEI***= Resource and Material Efficiency Index, ***RCI***= Recycled Content Index, ***RRI***= Reusability and Recyclability Index, ***DI***= Durability Index

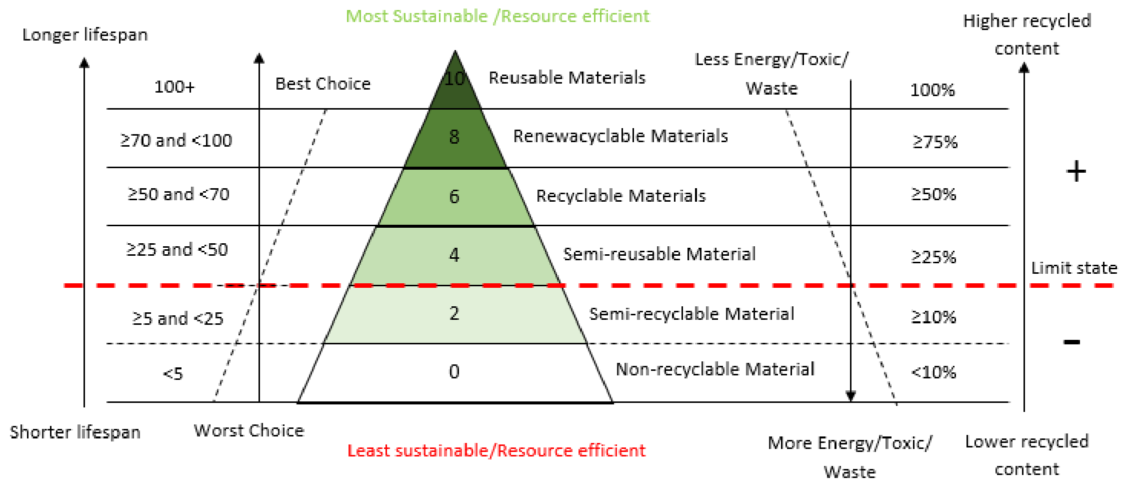


Figure 5-15: Resource-efficient building materials (resource efficiency index)

5.3.2 Socio-Economic Performance (SEP)

The construction sector has a strong effect on economic and social growths and it has a direct link with global environmental sustainability (Mateus & Bragança, 2011). The sector is facing increased demands from clients asking for high-quality buildings and materials with lower cost. Material selection is frequently influenced by cost constraints, local availability, and lack of technical knowledge. According to Castro-Lacouture et al (2009), materials reach up to 20–30% of the total building cost.

Historically, the material selection was largely based on the initial material cost and it is often set to the minimum. However, the life cycle cost (LCC) may be decreased by selecting materials with a higher initial cost. In some cases, the selection of low initial cost materials can have adverse impacts on quality, performance and environment, throughout the lifetime of the project. Thus, it is important to make a balance between the cost and the quality of building materials during the selection process.

Furthermore, green building materials aim to increase overall building performance and reduce environmental impacts and costs. Thus, environmental, health and well-being and economic aspects are considered throughout the life cycle of the building. Although many benefits have been noticed by applying green building materials, their initial cost has always been one of the most debated topics (Illankoon & Lu, 2019). However, other studies are claiming that it is necessary to examine the green building materials in a life cycle cost perspective rather than focusing on the initial materials cost to show the savings during the lifetime of the buildings (Bartlett, Howard, Bartlett, & Howard, 2000; Illankoon & Lu, 2019; J.-L. Kim, Greene, & Kim, 2014). In the field of building materials, a life cycle cost is an approach used to compare various material alternatives considering the life cycle cost and saving associated with each option.

According to Boussabaine and Kirkham (2004), the analysis of the life cycle cost of a building's component is effective in attaining sustainable targets specified for that building. The total life-cycle cost is the most appropriate cost to consider. Life cycle cost (LCC) in construction starts from the planning stage and end with the disposal and demolition stage; so-called cradle to grave analysis (Illankoon & Lu, 2019). These costs include the initial material costs, maintenance, replacement and demolition costs. According to Tam et al. (2017), key requirements of information are required to investigate the life cost of building materials. These include the capital cost of the building material, the application of the material within the building, the expected service life, the required maintenance work and the replacement and demolition costs.

On the other hand, the use of local building materials and local labours have the obvious benefit of cutting the overall construction cost by an easier construction process, low transportation cost and lower economic demands. Local building materials have the capability of creating buildings that are climatically, economically, and socially viable while reducing significant environmental impacts. However, both criteria have been used in the evaluation of the socio-economic performance of building materials.

5.3.2.1 Initial costs

The design, purchase, and construction costs are largely counted in the initial costs, which signify the current market prices (Illankoon & Lu, 2019). Initial costs are capital costs delivered for building construction, which contain the purchase of land, construction and financing costs. The initial cost represents the primary cost of materials life cycle cost. Materials and components with longest-serving cost more than those with short service lives, thus the design to lower the maintenance and operation costs may increase the material's upfront costs (Peter O. Akadiri et al., 2012).

5.3.2.2 Maintenance and replacement costs

The maintenance cost varies significantly depending on the conditions to which the material is exposed during its lifetime. For instance, the materials which are exposed to harsh weather conditions are expected to have more maintenance throughout their lifetime and then high maintenance cost is expected. Furthermore, each building material has different maintenance requirements, depending on the requirements of the system. The expected future maintenance cost can be obtained by the following formula (Blank & Targuin, 2012; Dwaikat & Ali, 2018; ISO, 2017; Tam et al., 2017):

$$\mathbf{FMC = PMC \times (1+r)^{n}} \quad \ldots\ldots(13)$$

Where:

FMC: future maintenance cost (value)

PMC: present maintenance cost (cost in the base year)

r: expected percentage of annual cost increase (real interest rate),

r= discount rate-inflation rate

n: number of years (between the base date and the occurrence of the cost)

Moreover, to reduce the uncertainty associated with predicting future inflation rates, it is recommended to consider the inflation rate and the discount rate throughout the life cycle costing assessment (Mohammed Kishk et al., 2003). The discount rate (also known as interest rate) is reflecting the time value of money and the associated risk, while the inflation rate referring to the continuous increase or decrease in the general price levels of goods and services. The discount rate refers to the equivalent value of a future amount of money. However, historical information about both rates can be obtained from regular reports normally issued by the department of statistics or other relevant bodies of the country (Dwaikat & Ali, 2018).

On the other hand, the replacement cost is the amount of money required to replace an existing material with the same quality at the present market price. Most likely the replacement cost will be higher than the price paid for the original materials. Thus, materials with a shorter lifespan need to be replaced eventually. Nevertheless, formula (14) can be also used to calculate this cost.

$$\mathbf{FRC = PRC \times (1+r)^{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where:

FMC: future replacement cost (value)

PMC: present replacement cost (cost in the base year)

r: expected percentage of annual cost increase (real interest rate),

n: number of years (between the base date and the occurrence of the cost)

4.3.2.3 Demolition costs

The demolition cost is an essential cost element of building life cycle cost. It is including the costs of inspection, demolition, disposing of material and any other costs associated with the disposal process. The demolition cost can be obtained by the following formula (Blank & Targuin, 2012; Dwaikat & Ali, 2018; ISO, 2017; Tam et al., 2017):

$$\mathbf{FDC = IDC \times (1+r)^{n}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Where:

FDC: future demolition cost (value),

PDC: present demolition cost (cost in the base year)

r: expected percentage of annual cost increase (real interest rate),

r= discount rate-inflation rate

n: number of years (between the base date and the occurrence of the cost)

In conclusion, the life cycle cost (LCC) of building material can be achieved from the following formula:

LCC= Σ IC+FMC+ FRC + FDC……………………………………………….….(16)

Where:

LCC= life cycle cost, ***FMC***= future maintenance cost, ***FRC***= future replacement cost, ***FDC***= future demolition cost

Materials with longer service life and lower LCC can be considered as the best alternative option[25]. An example of calculating LCC is shown in **Table 5-7**. The table shows how information can be entered for each material type. In the given example the expected service life of the material is set to be 35 years, while the expected service life of the building is 50 years. The following values are suggested for the example: the (r) value is 3%, initial material cost=30$, present maintenance cost= 25$, present demolition cost=20$. Therefore, the replacement of the material is expected to happen after 35 years and then the demolition at the end of the building lifetime.

Material A (35 years lifespan)					
Building Lifespan (50 Years)	**Initial Cost**	**Maintenance cost**	**Replacement cost**	**Demolition cost**	**Life cycle cost**
0	30$	-	-	-	30$
5	-	-	-	-	30$
10	-	-	-	-	30$
15	-	38.95$	-	-	68.95$
20	-	-	-	-	68.95$
25	-	-	-	-	68.95$
30	-	60.68$	-	-	129.63$
35	-	-	84.41$	56.28$	270.32$
40	-	-	-	-	270.32$
45	-	94.54$	-	-	364.86$
50	-	-	-	87.68$	452.54$
Total	30$	194.17$	84.41	143.96$	**452.54$**

Table 5-7: Example of LCC of material with a short lifespan

[25] The implementation of both Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) can assist project stakeholders to prove that they have considered the environmental and economic impacts of their decisions process and chosen the most appropriate building materials.

5.3.2.4 Locally available building material and Labour

The utilization of locally available materials in the construction industry generates several economic and sustainability advantages by reducing transportation costs and related energy and carbon emissions (Matalkah et al., 2017). Up to date, modern buildings are built from highly processed materials[26], seriously depleting natural resources (Ben-Alon, Loftness, Harries, DiPietro, & Hameen, 2019).

Over the last decade, several studies examined the possibility of integrating local materials into buildings. This include but not limited to adobe rammed earth, biomass ash, stabilized soil, stone, brick, natural pozzolans, bamboo, a tree trunk. However, their ability to withstand extreme climatic conditions is still subject to research. Furthermore, increase the use of local resource-based materials can increase the income chances and create jobs while developing the local construction industry and enhance the overall social and economic impacts. Besides, it keeps financing locally and saves on foreign exchange required to imports materials.

On the other hand, making use of the local labour force is seen as very essential to provide labour and social sustainability, aiming to reduce the percentages of unemployment and social exclusion. Besides, the use of local workforces can be considered the most effective way to achieve the basic features of a project. Therefore, the choice of adaptable, affordable and easily assembled building materials developed from locally available resources and can be constructed by local labours must be considered as major factors in the material selection stage.

In this part, the average life cycle cost has been considered as a base-value for assigning points for each building material type. The LCC, the availability of building materials and the availability of local labour to fix materials in the building have been considered as the main three factors affecting the socio-economic performance of the materials (Castro-Lacouture et al., 2009).

To sum up, the selection of building materials based on their socio-economic performance can be seen in **Table 5-8**. The table shows that higher points are assigned to building materials which their LCC below average and produced locally and can be installed by local labours, while lower points are assigned to building materials which their LCC

[26] Materials and products that are minimally processed (e.g., uncut stone, earth materials, wood, bamboo) often pose fewer ecological impacts.

above average, they aren’t produced locally and there are no available skilled labours to integrate them into buildings.

Locally available Material	Locally available labour	Life cycle cost (LCC) states	points
√	√	LCC below or equal to average	10
√	×	LCC below or equal to average	8
×	√	LCC below or equal to average	6
√	√	LCC above average	4
√	×	LCC above average	2
-	-	Other conditions	0

Table 5-8: A ranking scale for the selection of building materials based on their socio-economic performance

5.3.3 Health and Well-being (HW)

People spent more than 90% of their time inside buildings and this affects their physical comfort and psychological well-being (Al horr et al., 2016; ASHRAE, 2016; Shan, Melina, & Yang, 2018). The importance of human wellbeing in construction is badly recognized. Various comfort and health-related impacts are bound up with the characteristics of the building and it is components. In this regard, building materials have a direct impact on our well-being. In addition, materials can contribute to the poor indoor quality of the building with harmful effects on our health. Although there are extremely varied sources of pollutants that affect negatively the indoor built environment, materials have a large subset of them. See **Table 5-9**

In the past decade, an increasing body of environmental health studies has revealed that building materials, generally contain chemicals known or supposed to be hazardous to human health. Hazardous materials can affect both individuals and natural systems throughout the materials’ lifetime, during extraction, through manufacturing, installation, demolition and removal. The rising importance of sustainable and green building materials makes this subject a primary consideration, while offers a big opportunity for architects and designers to more carefully take into account the materials they select. Therefore, sustainable, green, non-toxic, healthy building materials must be selected from the preliminary design stages. Most of the previous studies are mainly focusing on energy, embodied carbon and resource efficiency factors affecting building materials, while the health and wellbeing aspects are barely considered.

Outdoor sources brought the environment	Consumer products used indoors	On-site equipment +furniture	Building materials and construction activity	Spaces use within or adjacent to the building	Inadequate maintenance
Tracked/ blown in dirt/ pollen/dust animal dander/ tobacco	Tobacco products	Office equipment	Plywood/ compressed wood	Laboratory	Heavily loaded filters
Local traffic	Art supplies	Cooking equipment	Construction adhesives	Medical office	Contaminated / shredded duct lining
Loading dock traffic	Pens & paper products	Upholstered furniture	Asbestos products	Hair/nail salon	Dirty drain pans
Construction dust	Personal products	Transformers	Insulation	Cafeteria	Condition of a mechanical room
Pest faecal matter	Print/ Photocopy	Humidifiers	Wall/floor coverings	Exhaust from the major tenant (e.g. dry cleaner)	Pools of stagnant water on a roof
Soil gas	Dry cleaning	Underground fuel storage tanks	Carpets/carpet adhesives	Trash and refuse area	Damp settings
Sewer gas	Solvents	Combustion appliances (boilers, stoves, furnaces, flues, generators)	Wet-applied building products	Cooling tower mist (pathogens, Legionella)	Faulty economizers
	Foodstuffs	Refrigerants	Painting, roofing, sanding	Restroom exhaust	Boilers/flues
	Cleaning products	Lubricants	Renovation/ remodelling	AHU relief vent	Pressure differentials
				Landscaping chemicals, fertilizers, etc.	Fan malfunctions

Table 5-9: common sources of pollutants that enter the indoor built environment

Adapted from (F. Yang & Tepfer, 2018)

The selection of healthier materials from an early stage within a project timeline will open more viable opportunities to explore alternatives across materials and assemblies to mitigate their chemical levels and negative impacts throughout their lifetime (see **Figure 5-16**).

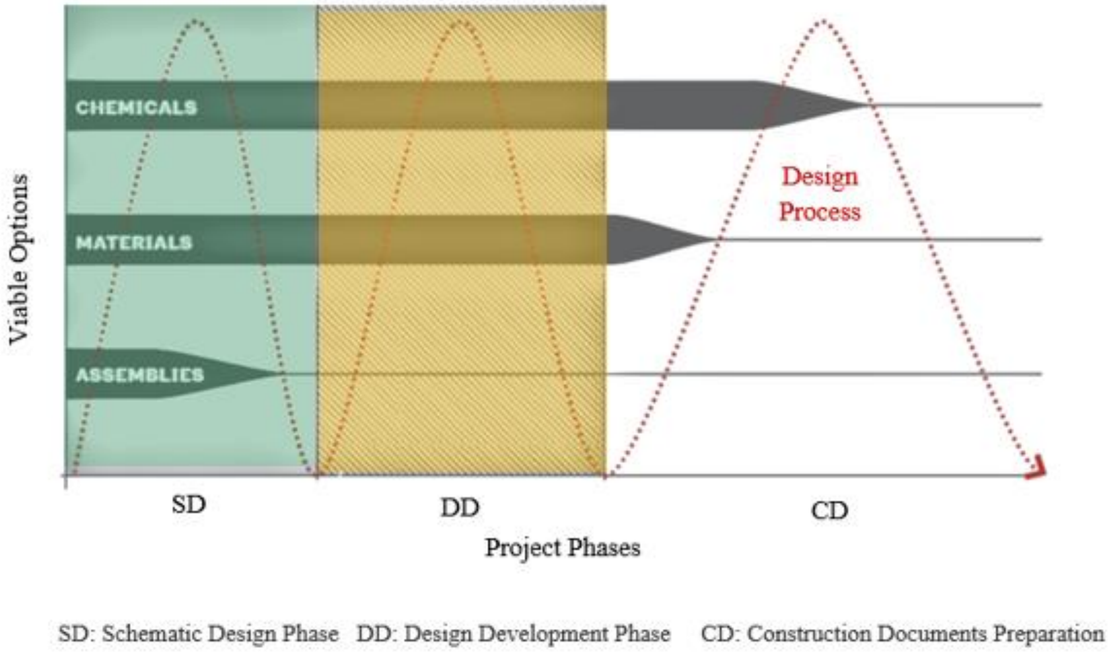


Figure 5-16: Viable options for considering healthier alternatives materials as the project is developed

However, building materials can contribute negatively or positively to the building and well-being in the following ways:

1. Materials can absorb or emit hazardous chemicals or volatile organic compounds (VOCs) which affect the air quality, human health and surrounding environment. (Red list /chemical avoidance list)
2. Materials can either stop or allow the transmission of moisture through the weather barrier and within the HVAC system. (Moisture management performance)
3. Materials with high fire-resistant quality can minimize or stop the spread of fire, allow people to evacuate safely, and reduce damage to the buildings.
4. Materials can store or emit CO_2 which contributes a great deal to greenhouse gas emissions and global warming.
5. Materials can play a major role to enhance the quality of visual and acoustic comfort of the indoor environment.

5.3.3.1 Red List / Chemical avoidance list

The red list also is known as the "chemical avoidance list", "restricted substances list," "banned list," or "blacklist" has been recently adopted in the construction industry for informing the selection of healthy materials. The concept of the red list is to avoid building materials and products that contain chemical substances that may have an adverse effect on human health. The red list is subject to change based on emerging scientific knowledge. However, project teams should reference the updated red list when speaking to product manufacturers about which substances are included in their products.

More recently, the majority of building environmental assessment tools have involved a component of health and environmentally conscious product and material selection. However, it acknowledges that while hazards can be reduced, not all hazards can be eliminated and that there is a significant amount of unknown information regarding the effects of various building materials and products on health and wellbeing. Normally the most difficult part about avoiding red list ingredients is finding the proper alternatives and getting the required information from manufacturers. However, these alternatives do not necessarily cost more than ordinary materials.

The restricted substances lists are developed from chemical hazard lists issued by government agencies, for example, the United States Environmental Agency (EPA)[27] and the European Union Commission on Environment[28]. There are several building industry red lists include Living Building Challenge (LBC) Red List, EPA Chemicals of Concern[29], WELL v1.0 Feature 25: Toxic Material Reduction[30], REACH SVHC Substances of Very High Concern) List[31], Cradle to Cradle Banned Chemicals List[32], Perkins and Will Transparency List[33] and LEED Pilot Credit 11: Chemical Avoidance list. However, the chemical avoidance lists are essentially unlimited and it is not an easy task to choose among them or how to rank them, which makes a confusing selection of

[27] This is an independent agency of the United States federal government for environmental protection, founded 1970.

[28] It was set up in 1973 to protect, preserve and improve Europe's environment for present and future generations.

[29] This list consists of chemical groups raising serious health or environmental concerns that have been flagged for EPA action. It aggregates four EPA lists.

[30] WELL is the leading tool for advancing health and well-being in buildings globally.

[31] The European Chemicals Agency (ECHA) maintains the REACH Substances of Very High Concern (SVHC) list, which is maintained per EU regulation

[32] Cradle to Cradle banned chemical lists is developed and managed by a non-profit group known as: The Cradle to Cradle Products Innovation Institute (C2CPII). It evaluates the performance of products in five impact categories: material health, material reutilization, renewable energy and carbon management, water stewardship, and social fairness.

[33] The List includes materials commonly found in the built environment that have been categorized as being harmful to human and/or environmental health. The list is updated as new information is announced. The tool is basically built in the concept of precautionary approach.

alternatives in real practice. Therefore, the common chemical lists which have been addressed amongst building industry red lists will be considered in this research.

On the other hand, there are also temporary red list exceptions for several blacklists substances for which possible alternatives are not yet available in the construction market. The commonalities, well-known and strongly suspected hazards among the lists have been included in **Table 5-10**.

• Halogenated Flame Retardants (HFRs)	• Asbestos
• Perfluorinated Compounds (PFCs)	• Lead
• Cadmium	• Mercury
• Volatile Organic Compounds (VOCs)	• Polybrominated diphenyl ethers (PBDEs)
• Creosote, Arsenic and Pentachlorophenol	• Formaldehyde
• Polyurethane	• Chlorinated Polyvinyl Chloride (CPVC)
• Polystyrene	• Bisphenol A (BPA)
• Chlorofluorocarbons (CFCs) and Hydro chlorofluorocarbons (HCFCs)	• Phthalates
• Chromium	• Polyvinyl Chloride (PVC)

Table 5-10: Common chemicals lists addressed amongst building industry red lists

Halogenated Flame Retardants (HFRs)

Flame retardants have been used extensively all around the world, mainly as an additive to reduce the flammability of materials to meet fire safety standards and rules (Dreyer et al., 2019). Halogenated Fire Retardants (HFRs) is a wide group of flame retardants that have roused concern in recent years. HFRs are persistent and bio-accumulative toxins, meaning that they accumulate in organisms and the broader environment, every so often making worryingly high concentrations as they travel up the food chain. Additionally, specific halogenated products have shown evidence of harm to humans and animal species. HFRs have been extensively applied in several commercial products, such as plastics, polymers, textiles (B. Zhu, Lam, & Lam, 2018) and almost all foam insulations (Dreyer et al., 2019).

Presently, there are four groups of flame retardants: inorganic, organophosphorus, halogenated organics, and nitrogen-based composites. Brominated flame retardants (BFRs) which is a subgroup of the halogenated organic class, are the most used flame retardants because of their low cost and high efficiency (Poma et al., 2018). HFRs include

PBDE, HBCD, TBBPA, Deca-BDE, TCPP, TCEP, Dechlorane Plus, and other retardants with bromine or chlorine.

Polybrominated diphenyl ethers (PBDEs) are an important class of flame retardants, widely used in building materials and a variety of consumer products including plastics, electronics and textiles. Many studies have shown the potential toxicity of PBDEs to fish, mammals, and human beings, such as reproductive toxicity, liver toxicity, neurotoxicity, and others (Jiang, Yuan, Lin, Ma, & Yu, 2019).

Perfluorinated Compounds (PFCs)

Perfluorinated compounds (PFCs) are a large class of synthetic fluorinated compounds and have been used in many industries including the construction industry. Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) are two of the best known PFCs. These compounds are thermally stable and can resist water, grease, and oil, which make them useful components in wide industrial products including metal coating and plating facilities, paints, firefighting foam, paper, waxes and polishes, and carpets (X. M. Wu et al., 2015).

Many of PFCs are greenhouse gases and bioaccumulate in the environment. PFCs have been detected in humans and animals, and they have been associated with increased cholesterol and uric acid, immune system effects, reduced human fertility, and cancer (X. M. Wu et al., 2015). Animal studies indicate damage to the liver and tumour development. Furthermore, some studies suggest that these substances may affect sex hormones and cholesterol in humans.

Chlorinated polymers, including PVC (Polyvinyl Chloride) and CPVC (chlorinated polyvinyl chloride)

PVC's vinyl chloride monomer building block is a known human carcinogen[34], due to its chlorine content. PVC often contains other Red List ingredients, such as cadmium, lead, and phthalates. In the construction industry, PVC is used in a wide range of applications such as pipes, wiring, films, profiles, sheets, fastening elements, flooring (vinyl), wallpaper, and coatings (Petrović & Hamer, 2018). The manufacture and disposal of chlorinated polymers can result in the production of dioxins and disposal phases.

[34] Carcinogens are defined as substances that cause or increase the risk of cancer. The International Agency for Research on Cancer (IARC) classifies substances as to carcinogenic risk into four groups; 1) the agent is carcinogenic to humans; 2A) the agent is probably carcinogenic to humans; 2B) the agent is possibly carcinogenic to humans; 3) the agent is not classifiable as to its carcinogenicity to humans; 4) the agent is probably not carcinogenic to humans.

According to the World Health Organization (2016a), dioxins are some of the most potent toxins known to humans, with no known safe limit for exposure and a strong propensity for bioaccumulation. Also, dioxins are highly persistent in the environment. Vinyl chloride can cause liver cancer (Natee, Low, & Teo, 2016).

Volatile Organic Compounds (VOCs)

Volatile Organic compounds (VOCs) are a group of organic chemicals that can affect the indoor (under ambient air conditions) and the outdoor air, causing serious environmental and health impacts. According to the United States Environmental Protection Agency (EPA), the average level of VOCs in homes is five times higher than outdoors. These chemicals have a high vapour pressure at room temperature and boiling points in an interval of approximately 50–100 °C to 240–260 °C (Kozicki, Piasecki, Goljan, Deptula, & Nieslochowski, 2018). Their health impact varies widely such as stratospheric O3 depletion, global climate change, and respiratory irritants to human carcinogens (Xufeng Zhang et al., 2019). However, on-site wet building materials such as paints, adhesives, and sealants are of particular concern since they can affect the health of labours who may not be using any kind of dermal protection.

Asbestos Compounds

Asbestos is a group of minerals that occur naturally in some rocks and soil. It has been widely used in a variety of construction materials because of its fibre strength and heat resistance. It is often used in wall insulation, vinyl floor coverings, paint compounds, roofing shingles, ceiling and floor tiles, paper products, and asbestos cement products. According to S. H. Park (2018), for building materials, approximately 10–20% asbestos is mixed with construction materials (ex. sand, cement and plaster) to produce new products (ex. cement corrugated sheets, cement flat boards, cement gypsum boards, and autoclaved cement extrusion panels).

Hazards of asbestos have been known since before 1980 (S. H. Park, 2018). The World Health Organization (2010) estimates that about 125 million people in the world are exposed to asbestos at the workplace, and at least 107,000 people die each year from asbestos-related infections. Exposure happens when asbestos fibres are released into the air during the use, demolition, work, building, or repair of asbestos-containing materials. Asbestos is a known human carcinogen, increasing risks of lung cancer, mesothelioma (a rare form of cancer that is found in the thin lining of the lung, chest and abdomen and heart), and asbestosis (a serious progressive, long-term, non-cancer disease of the lungs).

Although asbestos has been banned in many countries, other countries are still using it or materials containing asbestos (S. H. Park, 2018).

Formaldehyde

Formaldehyde is a colourless, flammable, strong-smelling volatile organic chemical that is used in building materials to manufacture many products. It is used in pressed-wood products, such as particleboard, plywood, and fiberboard; glues and adhesives; permanent-press fabrics; paper product coatings; and certain insulation materials. The harmful effects of formaldehyde on indoor air quality (IAQ) is therefore of serious concern (Z. Chen, Shi, Shen, Ma, & Xu, 2016). When formaldehyde is present in the air at levels exceeding 0.1 ppm (per cent per million), some people may suffer adverse effects such as watery eyes, nose, and throat; coughing; wheezing; nausea; and skin irritation. The international agency for cancer research classified formaldehyde as a known human carcinogen (Xiaojun Zhou et al., 2019). Formaldehyde acts as an asthma trigger while long-term exposure is associated with nasal cancers and leukaemia. Furthermore, formaldehyde is produced in small amounts by most living organisms as part of normal metabolic processes.

Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs)

Chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are strong greenhouse gases (GHGs). They induce stratospheric ozone depletion and their global warming potentials (GWPs) are much higher than that of CO_2 (J. Wu et al., 2013). According to the United Nations Environmental Protection Agency (EPA), the depletion of the ozone layer by CFC is responsible for an increased incidence of skin cancer, impairment of human immune systems, cataracts, and damage to wildlife. Although HCFCs are less harmful than CFCs, HCFCs are expected to be banned by the year 2030.

Bisphenol A (BPA)

Bisphenol A (BPA) is used in the manufacture of polycarbonate plastics and epoxy resins (N. Jalal, Surendranath, Pathak, Yu, & Chung, 2018). The plastics are used in many consumer products, such as plastic dinnerware, microwave ovenware, eyeglass lenses, electronics, car parts, and others, while epoxy resins are used in high-performance coatings (paints, floor sealers, and other protective coatings), floorings, drinking water storage tanks (Pelch et al., 2019) adhesives and fillers (caulk, grout, mortar, and putty), fibreglass binders, and cement additives. The majority of recent studies have shown the largest health-related impacts on the brains, behaviour, and prostate glands of fetuses, infants, and small children.

Wood treatments containing Arsenic, Creosote or Pentachlorophenol

Various conventional treatments are applied to wood to preserve it from decay and insects to increase its lifetime. These treatments present a series of human health and environmental problems. Creosotes are applied to prevent the wood from rot and it comes in a variety of types such as wood tar creosote, oil tar creosote, coal tar creosote, and water-gas tar creosote. The coal-tar creosote is the most toxic since it can cause cancer. Moreover, creosote exposure is closely related to skin and scrotum cancer in humans, and liver, kidney, and gestational problems in laboratory animals. Pentachlorophenol is extremely toxic to humans and it's connected with liver and immune system damage and other health risks. The US Environmental Protection Agency EPA (1984) has classified creosote and pentachlorophenol as chemicals that are potential carcinogens. Besides, Arsenic is used in wood treatment to stop insect attacks. According to Pandey and Singh (2015), Arsenic causes skin lesions, cancers and other symptoms in people who live nearby of arsenic exposures.

Toxic Heavy Metals

Toxic heavy metals (including lead, mercury, cadmium, and chromium (VI), and copper) are associated with several hazards to human health and the environment. Lead is a heavy metal, naturally occurring, non-degradable in nature, highly toxic at very low exposure levels and has a huge effect on human health and the environment (Njati & Maguta, 2019). A high level of exposure to lead can damage the reproductive organs, immune system, nervous system, liver, kidneys and cardiovascular system. Lead is commonly found in paints and roofing materials. They have been used as drying agents, fire retardants, corrosion restraint and pigments for colour or opacity in paints. Mercury is a naturally occurring and highly toxic metal found in rock in the earth's crust. Mercury is a worldwide chemical that causes hazards to ecosystems and human health (Steenhuisen & Wilson, 2019). Mercury produces a set of health effects, including harm to the nervous, digestive, and immune systems, and even death.

Cadmium is a heavy metal and one of the toxic metals classified as a category 1 human carcinogen (Reyes-Hinojosa et al., 2019). Cadmium carcinogen is associated with lung cancer, while intense and long-term exposures to it can cause lung and kidney damage, bone loss, and hypertension. Chromium is a naturally occurring element found in the air, water, and soil (Wise, Shi, & Zhang, 2019). Chromium III (trivalent chrome) is an essential nutrient, chromium (VI) (hexavalent chrome) can cause serious health issues, especially for factory workers who can inhale or ingest it during manufacturing. It can cause breathing problems as well as nasal and lung cancer. Chromium (VI) is used primarily for chrome plating of metals for decorative or protective finishes, making stainless steel, leather tanning, anti-corrosive agents for paints, and in textile dyes and pigments.

Finally, Copper is a very common substance that occurs naturally in the environment and spreads through the environment via natural phenomena. However, it generates toxicity at high exposure absorptions. Long-term exposure to copper can irritate the nose, mouth and eyes and it causes headaches, stomachaches, dizziness, vomiting and diarrhoea. Moreover, copper may cause liver and kidney damage and even death.

On the other hand, the state of knowledge of the chemicals hazards is incomplete and continually changing. In many cases, the avoidance of specific chemical concerns found in common building materials is used as an approach to eliminate or reduce the presence of these toxic substances. See **Table 5-11**

Furthermore, standards and guidelines related to indoor air pollutants levels are defined by various international agencies and organizations all around the world. Accordingly, researchers have employed these standards to evaluate the quality of indoor as well as outdoor environments. In this regard, the world health organization established a guideline regarding the concentrations of indoor chemical substances, and several countries have adopted them as regulations to control indoor air quality (Azuma, Kubo, & Isoda, 2015). For instance, Japan and China restricted the use of building materials containing formaldehyde of more than 0.08 ppm, while Korea and Singapore emphasizing the use of 0.1 ppm (120 µg/m^3) as 8–h average (Ahmed Abdul–Wahab, En, Elkamel, Ahmadi, & Yetilmezsoy, 2015). Also, 90 ppm has been introduced as the permissible limit of soluble lead in paints in many countries including the U.S, Canada, China, India, Nepal, Philippines, Tanzania, Kenya and the E.U (Njati & Maguta, 2019). However, this shows the necessity of adopting a general precautionary policy for controlling the use of all materials whether or not they are known to have any harmful effect.

Additionally, building industry rating systems have promoted the use of much material content disclosure and assessment tools, though in different ways. The most common options of the disclosure levels of chemicals contained within a given material are ranged from 100 ppm (0.01%) to 10,000 ppm (1%). Building materials with chemicals that are identified as health hazards are disclosed at 0.1% (1000 ppm) for carcinogens and 1% (10,000 ppm) for all other substances (Tristan & Melton, 2015).

Building Materials	**Common chemical substances**
Paints	Cadmium, BPA, VOCs
Protective coatings	PFCs, BPA, hexavalent chromium, VOCs
Adhesives	formaldehyde, phthalates, VOCs
Sealants	BPA, formaldehyde, phthalates, VOCs
Epoxy and resins	BPA, formaldehyde, VOCs
Insulation	halogenated flame retardants, formaldehyde, VOCs
Textiles	PFCs, VOCs
Wood treatment	Arsenic, creosote
Window treatment	PFCs, VOCs
Windows and doors	lead, hexavalent chromium, PVC
Composite wood products	Formaldehyde
Resilient floors	Formaldehyde, phthalates, PVC, VOCs
Carpets and backing	Formaldehyde, phthalates, VOCs
Flooring and backing	PFCs, formaldehyde, phthalates, PVC, VOCs
Polycarbonate plastics	BPA
Roofing	PFCs, phthalates, PVC
Waterproofing	Phthalates, PVC, VOCs
Siding	Arsenic, creosote, PVC
Wire and cable sheathing	Halogenated flame retardants, PVC
Electrical Devices	Halogenated flame retardants, lead, mercury
Piping	Lead, hexavalent chromium, PVC
Furniture (in general)	PFCs, formaldehyde, phthalates, PVC, VOCs

Table 5-11: Chemical substances found commonly in building materials

To sum up, choosing a healthy building material among options requires the identification of a benchmark scoring scale to show the percentages of chemical hazards associated with building materials commonly contain[35]. However, the weight of the hazardous chemicals in a certain material can be explained as ppm (part per million)[36] because different chemical materials can cause harmful effects at different levels of concentration. A higher "ppm" value corresponds to a higher concentration. **Figure 5-17** shows a

[35] Urgent hazard= arsenic, cadmium, halogenated flame retardants, lead, mercury, PFCs.
High hazards= BPA, creosote, hexavalent chromium, Formaldehyde.
Moderate hazards= phthalates, PVC and chlorinated plastics, VOCs.

[36] Parts Per Million (ppm) is commonly used as a unit of concentration. For very dilute solutions, weight/weight (w/w) and weight/volume (w/v) concentrations are sometimes expressed in parts per million.

scoring scale for assessing the health of building materials. The model is designed to be scalable and replicable for the stakeholders during the material's selection stage.

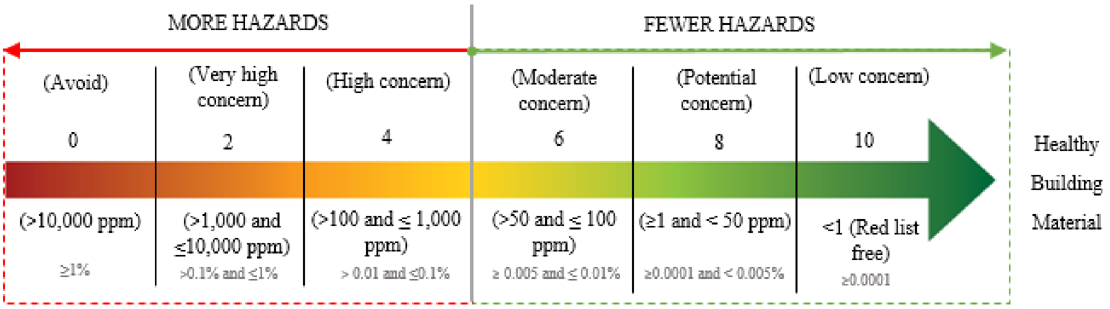


Figure 5-17: A benchmark scoring scale to evaluate materials options based on the percentages of chemical hazards associated with their use

The above score can be used to compare the product (material) against the score of an alternative product. It is recommended to select material when the spectrum shows only green or moderate yellow hazards.

5.3.3.2 Moisture Management Performance

Moisture can cause physical, chemical, mechanical, and biological deterioration that can lead to severe damage in buildings (Kreiger & Srubar, 2019). Hence, moisture control is essential to the efficient functioning of any building. Also, the control of moisture is crucial to protect inhabitants from harmful health effects associated with poor indoor air quality and to protect the buildings. The moisture content of the building materials is an important factor in mould growth, frost attack and other concerned problems (Kontoleon & Giarma, 2016). According to U.S. Environmental Protection Agency (2013), diverse effects have been noticed regarding the connection between damp or mouldy indoor environments and the development of harmful health impacts in exposed occupants, including upper respiratory (nasal and throat) symptoms, cough, wheeze, and asthma symptoms in sensitized persons with asthma.

In fact, moisture inside building materials[37] can have a range of damages to the structure of the building (durability), as well as the functional properties of the materials (thermal and energy efficiency) (Chwieduk, 2003; C. Feng & Janssen, 2019; Kreiger & Srubar, 2019). Although moisture problems are so common in buildings, many people consider them unavoidable. Furthermore, the moisture content of building materials is usually

[37] Some building materials might install wet because they were exposed to rain or plumbing leaks before/ during construction, while others are installed wet because water is part of the process.

stated as the percentage of the weight of water in the material relative to the weight of the dry materials. It can be calculated by weighing the test sample while wet, then drying the sample using heat or desiccant salts, and afterwards reweighing the sample. Few studies provide evidence on the moisture content data which could be used as a guide reference in this research. The moisture content of building materials can be expressed by the following formula:

% Moisture content = ((wet weight – dry weight) / dry weight) x 100 %......................(17)

On the other hand, porous materials (e.g. wood products) and damp porous materials (e.g. concrete products) are vulnerable to mould growth if their moisture content is too high. Some building materials require an addition of water during their installation (e.g., concrete, water-based coatings, wet-spray fireproofing and wet-spray insulation). These materials may not deteriorate from the long exposure to moisture but as they dry, they will transfer their moisture to close by materials which can further the growth of mould or alter their properties (U.S. Environmental Protection Agency, 2013).

Building materials should not be applied in the construction until their moisture content is below a specified percentage. For example, 5.5% of moisture content is used by some product manufacturers to indicate whether the concrete is dry enough to allow their products to be applied to it or not. In this line of thought, the United States Department of Agriculture (2010) recommends average moisture content of 15% or less, with a maximum of 19% or less to avoid dimensional changes concerns associated with the use of wooden materials. Moreover, according to Goetzke-Pala and Hoła (2016), brickwork with more than 12% of moisture content can be considered very damp. However, the selection of moisture-resistant materials can mitigate these problems.

Table 5-12 shows acceptable moisture levels for selected building materials prepared by William Yobe & Associates & U.S. Forest Products-USDA (2010).

Building Material/Component	Acceptable Moisture Content %
Baseboard	7-10
Gypsum Wallboard	7-10
Hardwood Flooring	7-10
Framing Lumber	15-19
Wood Furnishings (Interior)	7-12

Table 5-12: Acceptable Moisture Content for select building materials

Adapted from William Yobe and Associates & U.S. Forest Products-USDA (2010)

The selection of moisture-content materials is very important for the constructions since larger water contents can increase their degradation rate (Maksimović et al., 2012). In fact, previous research has reported that up to 90% of all construction material and building durability issues are created by moisture (Kreiger & Srubar, 2019). **Figure 5-18** shows a point system to range building materials based on their moisture content.

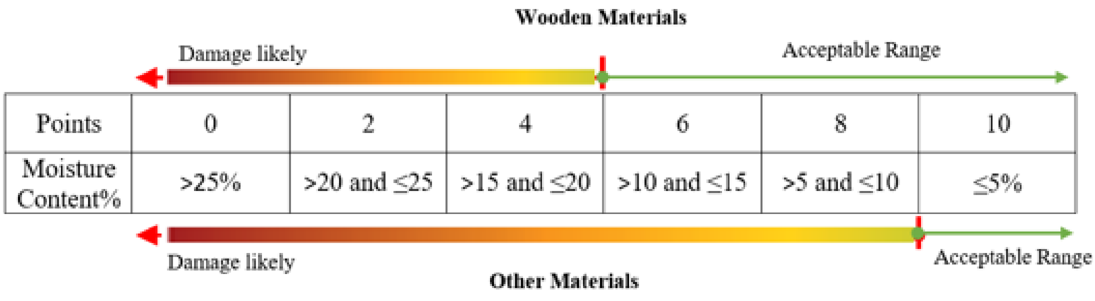


Figure 5-18: A point system to evaluate building materials based on their moisture contents

5.3.3.3 Fire resistance performance

Recently, a fire has become a major disaster in buildings due to the increase in fire loads, as a consequence of modern furniture and lightweight construction. The results from uncontrolled fire incidents are huge for human life as well as human assets. Fire causes enormous disaster putting at risk the lives of many people and having massive economic consequences (Panias, Balomenos, & Sakkas, 2014). Besides, it negatively affects the function and sustainability of buildings and can cause significant damage to building structures (Rahardjo & Prihanton, 2020).

Fire-resistant is the property of material or assembly to resist high-temperature treatment without damage. Fire-resistance rating (FRR) is considered as the fire performance indicator, and it is typically determined by measuring the ability of material or assembly to withstand standard material test (Panias et al., 2014). It can be quantified as a measure of the time in respect to how long it would take fire to affect the material's structural abilities (for example ½, 1, 2, 4 hours). It simply takes longer for the fire to affect fire-resistant materials.

Fire-resistance rating (FRR) of building elements has been commonly determined using standard fire tests specified in ISO 834 or ASTM (Ariyanayagam & Mahendran, 2019; Gernay, 2019). **Figure 5-19** shows the time-temperature curve of the ISO 834 standard fire in the fire tests

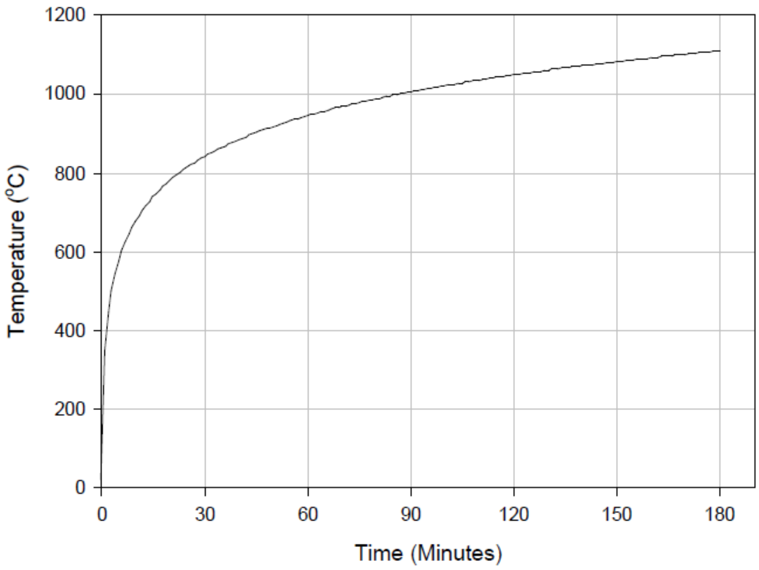


Figure 5-19: ISO 834 standard temperature-time fire curve

Nearly all European countries have standards similar to ISO 834, while the United States and other countries are applying ASTM E119 (A. H. Shah & Sharma, 2017). Currently, there is a wide-growing consciousness amongst the architects and engineers to keep the safety of the occupants as the focus in the event of a fire, and most of the countries initiated codes and standard fire resistance tests for rating the resistance of materials before integrating them into the building.

An emphasis on the resistance to fire is a large component of building code regulations. The Building Code of Australia (BCA) specifies certain Fire Resistance Levels (FRL) for construction elements to be able to provide fire compartmentation (Australian Building Codes Board, 2016). The Australian code defined the FRL as the grading period in minutes for three criteria: structural adequacy, integrity and insulation, tested to AS 1530.4-1990: "*Methods for fire tests on building materials, components and structures – Fire-resistance tests of elements of building construction*".

Structural adequacy means the ability of a structure to maintain its stability and loadbearing capacity; Integrity means the ability of a structure to resist the passage of flames and hot gases and Insulation means the ability of a structure to maintain a temperature below specified limits on the surface not exposed to fire. Hence, an FRL requirement for a wall of 60/60/60 means that the wall must maintain structural adequacy for 60 minutes, integrity for 60 minutes and insulation for 60 minutes. The required FRLs can be 30, 60, 90, 120, 180 or 240 min for both load-bearing and non-load-bearing walls depending on the class of building (Dodangoda, Mahendran, Keerthan, & Frost, 2019).

Furthermore, within the US, each state and some cities adopt one or more model building codes. The load-bearing structure (include columns, beams, floors and load-bearing walls) are required to have a 60 mins FRR for buildings that have four floors or more in height. Also, if the building is a high rise building (bearing more than 22.9m in height), it requires a 120-180 mins FRR (Barber, 2017). In the same line, the building codes for fire safety of Japan assigned technical criteria to evaluate the fire-resistive performance of various construction parts based on their location within the building, for example, 60 mins FRR is essential for loadbearing walls, columns, floors and beams in the uppermost story and second to fourth stories from the uppermost story, while 180 mins FRR is required for columns and beams in the fifteenth story or more from the uppermost story. **See Table 5-13**

Story / Parts	(1) Uppermost story and second to fourth stories from the uppermost story	(2) Fifth to fourteenth stories from the uppermost story	(3) Fifteenth story or more from the uppermost story
Load-bearing walls	I hour	2 hours	2 hours
Columns	1 hour	2 hours	3 hours
Floors	1 hour	2 hours	2 hours
Beams	1 hour	2 hours	3 hours
Roofs		0.5 hour	
Stairs		0.5 hour	

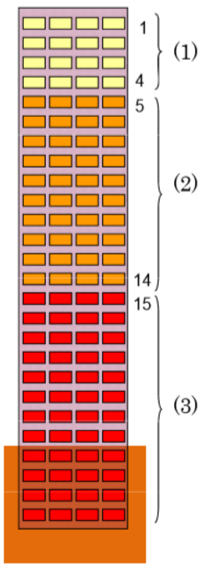


Table 5-13: Technical criteria of fire-resistive performance required on the building parts of fire-resistive construction-Building Regulation in Japan

Adapted from (The Building Center of Japan, 2013)

Generally, high-rise buildings are required to have an increased level of fire protection and structural performance than low rise building. Medium and high-rise buildings across the globe require an FRR that ranges from 60 mins up to 120 mins, depending on the country and applied code (Barber, 2017). However, the key is to select a material or assembly in which a fire would take effect slowly, allowing the occupants plenty of time to escape (the longer the time, the higher the fire-resistive performance). For a building to be considered fire resistive (FR), the main structural members including beams, columns, floors, roofs, and load-bearing walls must have a higher fire-resistance rating than the secondary members (those not affecting the stability of the structure) and nonbearing walls.

Each building material has unique fire resistance characteristics and the differences in fire performance between various materials can be evaluated by comparing flame spread ratings and heat release rate. There are several fire-resistant materials used in the construction of various buildings. Among them, concrete and gypsum wallboards (drywall) are commonly known as fire resistant and incombustible materials (Mróz, Hager, & Korniejenko, 2016).

Furthermore, fire resistance is typically associated with an assembly construction and therefore considers the performance of several materials that would be integrated into a wall, floor or roof. **Figure 5-20** shows a point scale to rank building materials and construction assemblies based on their fire-resistance rating in the event of a fire.

Structural elements/or loadbearing walls for low rise building (4 stories or less)

Structural elements/or loadbearing walls for medium and high rise building (more than 4 stories)

FRR (minutes) Main structural members and bearing walls	<60	≥60 and <90	≥90 and <120	≥120 and <150	≥150 and <180	≥180
Points	**0**	**2**	**4**	**6**	**8**	**10**
FRR (minutes) Secondary members/single layer materials and roofs	<20	≥20 and <30	≥30 and <40	≥40 and <50	≥50 and <60	≥60

Roofing materials

A range for single layer materials

Non-bearing assemblies must have a fire resistance rating of not less than 1 h (60 Mins)

Figure 5-20: A fire-resistance rating scale to rank building materials and their assemblies

<u>5.3.3.4 Embodied Carbon</u>

The fast growth of urban populations instincts demands more construction materials for new buildings, extensions, refurbishment, and infrastructure (Bionova Ltd/One Click LCA, 2018). This generates significant and direct carbon emissions before the accomplishment of the projects. As buildings become more energy efficient, the significance of embodied carbon only raises. Embodied carbon is irrecoverable, as it is emitted before the use of the building (L. Huang, Krigsvoll, Johansen, Liu, & Zhang, 2018). The greatest prospect for impact on embodied carbon comes at an early design stage[38], in particular in the selection of building materials. If chances are not taken at this phase, the embodied carbon savings will become more challenging and more costly for the entire lifetime of the building. **Figure 5-21** shows the continuous growth of the embodied carbon over time.

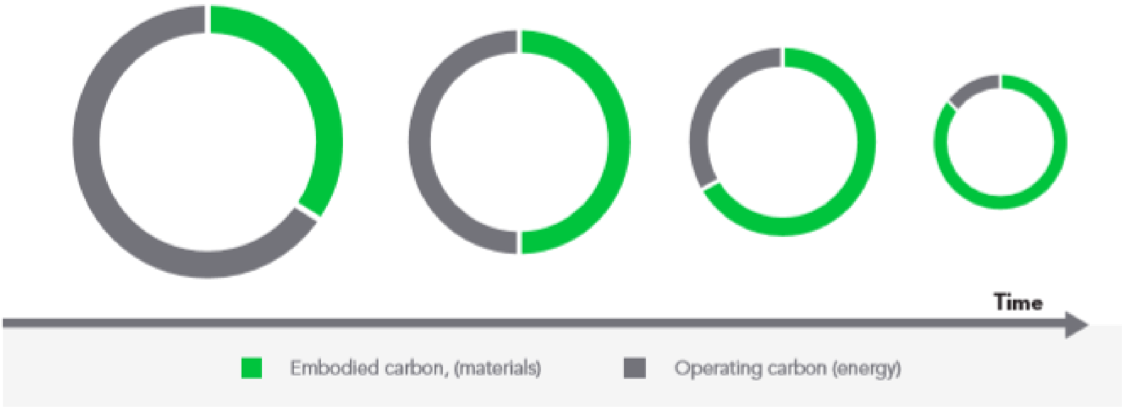


Figure 5-21: Embodied carbon's importance continues to grow

Adapted from (Bionova Ltd/One Click LCA, 2018)

Building and construction are responsible for 11% of the global carbon emissions that are associated with materials and construction processes throughout the building lifecycle (World Green Building Council, 2019). Moreover, Building materials can contribute to approximately 42% of the life cycle carbon[39] emissions in buildings (Kofoworola & Gheewala, 2008), while Carbon dioxide (CO_2) contributes to about 80% of the global warming effect (IPCC, 2007). The construction industry is highly distributed and relies on a wide range of materials with long and multifaceted supply chains. Several building materials are used in constructions and each consumes energy and emit carbon at different level throughout their lifetime (many of the widely used construction materials are from carbon-intensive heavy industries). Nevertheless, embodied energy and embodied carbon is regarded as equally significant in the context of building materials. For instance, the use of alternative materials that require a small amount of energy (such as wood) will reduce both the embodied energy and carbon in the building. As a general rule, building materials with high embodied energy could result in more carbon emissions than materials with low embodied energy. However, selecting low-carbon building materials

[38] The upfront emissions from materials used to construct buildings and those installed later throughout maintenance and renovation, typically represent a significantly greater source of embodied carbon than all other stages in the lifecycle. They will be responsible for 50% of the entire carbon footprint of new construction between now and 2050.

[39] Building rating systems such as BREEAM, LEED and Green Star all identify embodied carbon measurement and mitigation as part of minimizing building life cycle impacts.

is considered a key factor to mitigate carbon emission in buildings (Pacheco-Torres et al., 2014; Zuo, Read, Pullen, & Shi, 2012). The Life Cycle Carbon embodied emissions of material (m) can be obtained from the following formula (Chau, Leung, & Ng, 2015):

$$\mathbf{CO_{2,\ embodied,\ i} = CO_{2,\ extraction,\ i} + CO_{2,\ manufacture,\ i} + CO_{2,\ transportation,\ i}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

Where $\mathbf{CO_{2,\ embodied,\ i}}$ is the embodied carbon emission of the ith material; $\mathbf{CO_{2,\ extraction,\ i}}$ is carbon emissions due to extraction; $\mathbf{CO_{2,\ manufacture,i}}$ is the carbon emissions due to manufacturing process of the ith material; $\mathbf{CO_{2,\ transportation,\ i}}$ is the carbon emissions associated with ith material transportation at the end of its lifetime.

Furthermore, the embodied carbon content of materials (m) can be obtained from the following equation (Sandanayake, Zhang, Setunge, Li, & Fang, 2016):

$$\mathbf{E_m = \sum Q_m \times e_m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

Where $\mathbf{E_m}$ is the embodied emission of material m used in the construction in $kgCO_2$-eq, $\mathbf{Q_m}$ is the amount of m^{th} material used in kgs and $\mathbf{e_m}$ is the carbon-equivalent emission factor for m^{th} material in $kgCO_2$-eq/kg (extracted from an appropriate carbon emissions database).

Embodied Carbon Coefficients (ECC) are expressed in kg of CO_2e ($kgCO_2e$) per kg of material (kgm), where CO_2e stands for the equivalent in carbon dioxide of the greenhouse gases (GHG) produced for the manufacturing and transportation of these materials. Universally, cement and steel[40] are two of the most important sources of material-related emissions in construction. These materials require very high temperatures during manufacture, making them energy-intensive and, in both cases, the chemical reactions that take place during production also emit carbon dioxide bluntly. According to Kumanayake, Luo, and Paulusz (2018), materials with high mass quantities (such as concrete and bricks) and materials with high carbon intensities (such as aluminium and glass) are the main two categories that need special focus during the materials selection procedure. This indicates that materials used in big quantities can contribute significantly to the carbon footprint of the building even though their embodied carbon coefficient values are low.

[40] Cement manufacture is responsible for about 7% of global carbon emissions, while steel impacting 7-9% of the global total, particularly around 50% can be assigned to buildings and construction.

Table 5-14 gives values of the embodied carbon of some building materials extracted from (Dimoudi & Tompa, 2008; Kumanayake et al., 2018; Pacheco-Torres et al., 2014; University of Bath, 2011; Xiaocun Zhang & Wang, 2015).

Material	**Embodied carbon coefficient ($kgCO_2/kg$)**	**Material**	**Embodied carbon coefficient ($kgCO_2/kg$)**
Ready-mixed concrete	0.123	Galvanized iron	2.03
Reinforcement steel	1.86	Gypsum board	0.39
Clay bricks	0.24	Mineral fiberboard	1.042
Structural steel	2.03	Ceramic tiles	0.78
Cement plaster	0.182	Cement mortar	0.15
Aluminium	9.16	Glass	1.40
Paint	2.91	Random rubble	0.7

Table 5-14: Values of embodied carbon coefficients

The materials' embodied carbon may differ greatly depending on many factors; for instance the type of the raw material, the location of material quarries and mode of transport needed, and carbon intensiveness of extraction and processing. Moreover, the majority of data sources offer broad building material information. This information can enable the identification of alternative materials to reduce embodied impacts. For instance, data on embodied carbon and energy for building materials and elements can be found in the following sources (UK Green Building Council, 2015):

I. Inventory of Energy and Carbon (ICE) database (building materials database developed at the University of Bath presenting average values developed through a review of a range of studies, available to download in excel).
II. European Reference Lifecycle database (life cycle inventory data collected from EU associations and other sources for materials, energy carriers, transport and waste management).
III. SteelConstruction.Info holds generic figures for brick, concrete and steel.
IV. WRAP embodied carbon database - data and benchmarks covering all life cycle stages.
V. Wood for Good Lifecycle Database holds generic information for timber, timber products and panels.
VI. BRE Global Green Guide to specification (database of generic environmental impact data on building materials, components and elements).

VII. BRE Global Green Book live (database of manufacturer specific data on products and services).

Although it is challenging and highly uncertain, selecting low embodied-carbon building materials from an early design stage will create a range of prospects to achieve the highest emissions reduction in buildings and contribute to the establishment of databases and help set benchmarks. However, alternative building materials can be ranked and selected based on their embodied carbon coefficient (Cradle to gate approach).

Figure 5-22 shows a system boundary for ranking building materials based on their embodied carbon intensities.

Points	0	2	4	6	8	10
Embodied carbon coefficient (kgCO_2/kg)	>2.5	>2 and ≤2.5	>1.5 and ≤2	>1 and ≤1.5	>0.5 and ≤1	≤0.5

Figure 5-22: Scoring scale for ranking building materials based on their embodied carbon coefficients

The proposed scale has been based on a model that the embodied carbon coefficients of most building materials are below 5 kgCO_2/kg except for Aluminum and other metals which can reach up to 9.16 kgCO_2/kg (with an average of 2 kgCO_2/kg). Accordingly, the above scoring method has been designed as a conceptual embodied carbon estimator that is reasonably accurate and does not require a complicated calculation during the early design stages.

5.3.3.5 Visual and thermal comfort

Visual comfort is an important aspect of good indoor environmental quality in buildings which can be achieved by artificial lighting or by daylighting (Giarma, Tsikaloudaki, & Aravantinos, 2017). The European standard EN 12665 (2011b) defined visual comfort as "a subjective condition of visual well-being induced by the visual environment". According to Carlucci, Causone, De Rosa, and Pagliano (2015), the amount of light, uniformity of light, quality of lights, and predicting the risk of glare are considered as the main physical factors which all together define visual comfort.

Furthermore, the finishing and colour of building materials are the most important factors that directly affect the quantity and the quality of light. For instance, materials with light colours have higher reflection factors than materials with dark colours (light colours have lower absorption and hence reflect more light). As a matter of fact, it is necessary to consider surface solar reflectance as one of the main parameters to optimize the reflection and distribution of natural light and electric lights (illuminance level) in the indoor spaces (Makaremi et al., 2017). In this regard, solar reflectance (SR) can be defined as the proportion of solar radiation reflected by a body or a surface to the incident amount upon it. SR is one of the main parameters that affect the illumination level of the indoor space as well as the heat transfer through the opaque building envelope and cooling energy consumption. The European Committee for Standardization-EN 12464-1 (2011a) has recommended the following scales of useful reflectance for major interior surfaces (walls, floor and ceiling):

- Ceiling: 0.7 to 0.9
- Walls: 0.5 to 0.8
- Floor: 0.2 to 0.4

On the other hand, building materials used for the external finishes (façade and roof) with high solar reflectance and thermal emittance (also called infrared emittance, or thermal emissivity) can reduce the temperature of the surfaces, and consequently saves electricity and reduces power demand during peak hours by decreasing the need for air conditioning in warm weather. (Akbari & Matthews, 2012; Paolini, Zani, Poli, Antretter, & Zinzi, 2017). (See **Figure 5-23**)

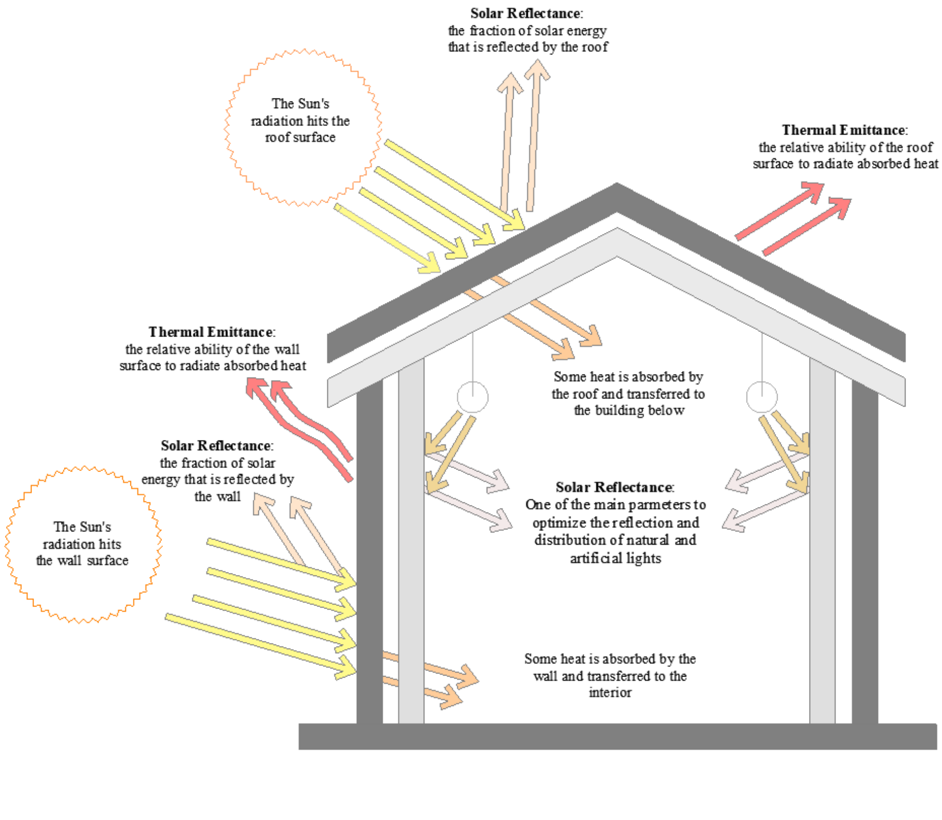


Figure 5-23: Understanding the material’s solar reflectance and thermal transmittance

Determination of solar reflectance and thermal emissivity, and subsequent calculation of the relative temperature of the surfaces with respect to black and white reference temperature defined as the Solar Reflectance Index (SRI). SRI can be considered as a better indicator of how building materials behave once solar radiation is incident on their surfaces. SRI has found a strong interest in the construction sector given its effectiveness in the demonstration of the surface behaviour of building materials. According to the ASTM E1980-01 (2011), the SRI measures how hot a flat surface of materials would get relative to a standard black (reflectivity 5%, emissivity 90%) and a standard white surface (reflectivity 80%, emissivity 90%). SRI is a scale from 0 to 100 on which materials that absorb and retain solar radiation have a lower number, whilst highly reflective materials have a higher number. Generally, materials that have both high solar reflectance (SR) and high emissivity value will result in a building with greater thermal efficiency, improve occupants comfort and reduce cooling load accordingly.

The SRI can be obtained by the following equation:

$$SRI = 100\frac{(Tb - Ts)}{(Tb - Tw)} \qquad \text{(20)}$$

In Equation 20 **Ts** is the steady-state surface temperature (K), (**Tb and Tw**) are the steady-state temperature of references black and white surfaces. According to ASTM E1980-01 (2011), for a surface exposed to the sun, when the conduction into the material is zero, the steady-state surface temperature (**TS**) is obtained by Equation 21.

$$Ts = 309{,}07 + \left(\frac{1066{,}07\alpha - 31{,}98\varepsilon}{6{,}78\varepsilon + h_c}\right) - \left(\frac{890{,}94\alpha^2 + 2153{,}83\alpha\varepsilon}{(6{,}78\varepsilon + h_c)^2}\right) \qquad \text{(21)}$$

Additionally, in accordance with ASTM E1980-01 (2011), under the standard solar and ambient states, Equation 22 is reverted to:

$$SRI = 123.97 - 141.35\chi + 9.655\chi^2 \qquad \text{(22)}$$

$$\chi = \frac{(\alpha - 0.029\varepsilon)(8.797 + h_c)}{9.5205\varepsilon + h_c}$$

Where: α = solar absorptance (1 - ρ), ρ = solar reflectance, ε = thermal emittance, h_c = convective coefficient (W.m-2. K-1).

Moreover, the concept of cool materials (cool roofs and cool walls) has been considered as one of the lowest costs and viable alternative strategy for mitigating the problem of urban heat island in many countries (Alchapar, Correa, & Cantón, 2014; Košir, Pajek, Iglič, & Kunič, 2018). According to Hosseini and Akbari (2016) and Pisello, Castaldo, Piselli, Pignatta, and Cotana (2015), negligible wintertime heating penalties for cool materials (roof and façade) have been noticed in cold climates[41]. External building materials with high SRI are recommended widely without much regard for climate or project limitations. In fact, cool materials have high thermal emittance and higher solar reflectance properties compared to conventional construction materials since they reflecting solar radiation and emitting the absorbed energy back to the atmosphere (Piselli et al., 2017). See **Table 5-15**

Material	**Infrared emittance**	**SR (%)**	**SRI (%)**
Composite Alum-Gray	0.89	71	87
Aluminium–zinc panel	0.87	57	68
Bituminous roofing felt	0.87	23	21
Concrete tile, white	0.90	73	90
Concrete-cool coating	0.90[42]	70-88	86
Asphalt shingles, white	0.91	21	21
Interlock-Red	0.80-0.90	55	64
Interlock-Yellow	0.85-0.90	58	68
Sandstone-Light brown	0.90-0.93	45	52
Limestone-White	0.90-0.93	55	65
Limestone-Yellow	0.90-0.93	45	52
Granite-Black	0.85-0.95	19-25	15
Granite-Gray	0.85-0.95	20-30	23
Marble-Black	0.90-0.93	20-25	19
Marble-White	0.84-0.93	55	63
Ceramic-White	0.85–0.94	72–77	88
Ceramic-Blue	0.85–0.94	22-40	19
Ceramic- glazed green	0.88-0.95	27-30	26

Table 5-15: Optical properties of various construction materials[43]

Adapted from (Natural Stone Institute, 2009; Hassan Radhi, Assem, & Sharples, 2014)

Cool materials can lower the heat released to the indoor ambient air and the outdoor urban environment. However, SR and SRI allow a direct comparison between various building

[41] In cold climates, during the winter the sun angle is lower, days are shorter, sky is cloudy (, and most heating occurs during early morning or evening hours when the solar intensity is low. Also, the roof may be covered with snow for most of the heating season.

[42] Non-metallic opaque building materials such as masonry, concrete, and wood have an emittance of 0.90 (ASHRAE 2005).

[43] In several countries the regulations on solar reflective materials are still under development and only initial values of surface properties are considered (Muscio, 2018).

materials with different optical properties (solar reflectance and emissivity), which allow designers to choose the appropriate materials to make energy-efficient and comfortable buildings. On the other hand, minimum SR and SRI values are specified in few countries by rules on building energy efficiency such as Title 24 of California (California Energy Commission, 2015), as well as by voluntary rating systems like LEED (under sustainable sites credit); those values are usually differentiated for low-sloped and steep-roofs and for building use. For instance, initial values of SRI ≥ 39 for steep-sloped roofs[44], SRI ≥ 82 for low-sloped roofs[45], and SRI ≥33 for non-roof surfaces are required in the LEED rating system (Muscio, 2018). Additionally, Title 24 of California require minimum values of both solar reflectance and thermal emittance higher than 0.75 for the latter unless conformity is proved for their combination through the SRI (California Energy Commission, 2015). Moreover, Energy Star (2013) sets a minimum SRI requirement for cool roofs; low-sloped roofing products required to have initial and three-year-aged solar reflectance not less than 0.65 and 0.50, respectively. Steep-sloped roofing products must have initial and three-year-aged solar reflectance not less than 0.25 and 0.15, respectively. In brief, the determination of solar reflectance (SR) and solar reflectance index (SRI) of surfaces with respect to the reference temperature of a black and white pattern could help to choose adequate materials for energy consumption efficiency and indoor thermal comfort of the buildings. **Figure 5-24** shows a scoring scale to rank building materials (internal and external finishes) based on their solar reflectance and solar reflectance index values.

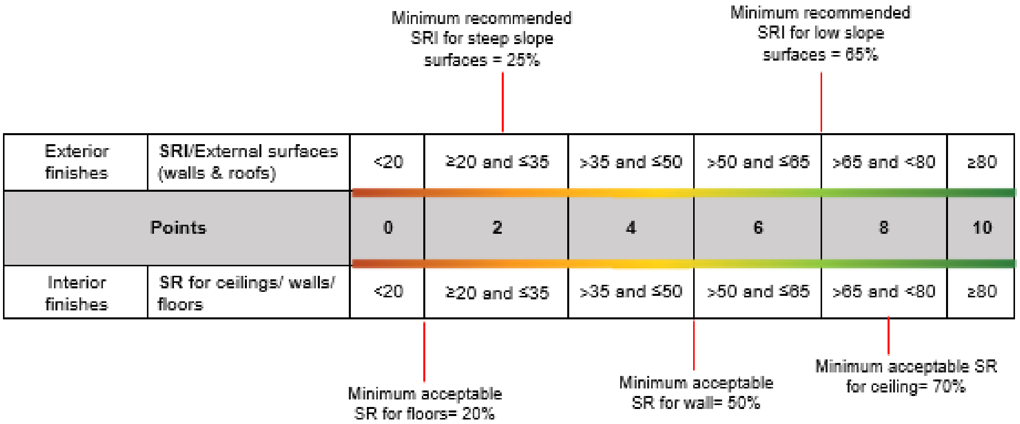


Figure 5-24: A scoring scale for ranking building materials based on SR and SRI values

[44] Steep-Slope Roofs: Surfaces with a slope greater than 2:12.
[45] Low-Slope Roofs: Surfaces with a slope of 2:12 or less.

5.3.3.6 Acoustic Comfort

Over the past decade, noise pollution has become the most well-known and least measured environmental issue (Talebi, Soltani, Habibi, & Latifi, 2019). Exposure to a high level of noise may affect human health and well-being by introducing heart diseases, annoyance, sleep disturbance, concentration loss, irritability and also long-term health effects, such as cardiovascular disease, heart illness, hypertension and psychiatric problems (Altomonte, Rutherford, & Wilson, 2015; Bhingare et al., 2019; Claudi, Arnesano, Chiariotti, Battista, & Revel, 2019; World Health Organization (WHO), 2018; Zannin & Ferreira, 2007).

All building materials have some acoustical properties; once the sound waves meet the surface of the material: part of it reflects; other permeates, and the remainder is absorbed by the material itself (Woodhead Publishing, 2011). Therefore, the employment of active sound-absorbing material with a higher sound-absorbing coefficient value (α alpha) is considered an effective way to solve these concerns and improve the acoustic quality of the built environment (Vitkauskaite & Grubliauskas, 2018).

Furthermore, the thickness and surface of the materials[46] , the density[47] as well as the incident angle and frequency of the sound waves are the main factors affecting in material's sound absorption. The ratio of the energy absorbed by the surface to the incident energy is called sound absorption coefficient (∝) which can assume values in a range from 0 (totally reflecting surfaces) to 1 (totally absorbing surfaces). For instance, if 30% of the incident sound is absorbed and 70% is reflected, the sound absorption coefficient of the material is 0.30. The sound absorption coefficient (∝) can be obtained by the following formula:

$$\alpha = \frac{E}{E_0} \qquad \text{(23)}$$

Where: $\propto$ is the sound absorption coefficient; ***E*** is the absorbed sound energy (including the permeating part); E_0 is the incident sound energy.

Furthermore, the sound absorption coefficient increases with increasing porosity (the volume of the voids/holes to the total volume). Efficient sound absorbers materials show

[46] The thickness of the materials is only relevant or has a direct relationship at low-frequency range (100-2000Hz) and is insignificant for high frequency (>2000Hz).

[47] With increasing of the material's density, the sound absorption coefficients slightly increased in the low frequencies' range and the absorption efficiency to high frequency sound decreases.

values of porosity[48] close to one (Luisa F.Cabeza, Anna L.Pisello, & Federica, 2019). The sound absorption coefficient of materials is correlated with frequency, and it varies with different frequencies. Normally, six frequencies[49] are used to reflect the sound absorption coefficient of one material systematically (125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz). Afterwards, the sound absorption average (SAA) of the six frequencies is used as a sound absorption coefficient of the material. SAA is also referred to as the Noise Reduction Coefficient (NRC) (Echeverria et al., 2019). Generally, if the average value (NRC) is more than 0.2, the material can be classified as a sound-absorbing material [50](Woodhead Publishing, 2011). See **Table 5-16**

Material	**Frequency, Hz**						
	125	250	500	1000	2000	4000	**NRC**
Walls							
Plaster, 7/8″, gypsum or lime, on brick	0.01	0.02	0.02	0.03	0.04	0.05	**0.03**
Plaster, on concrete block	0.12	0.09	0.07	0.05	0.05	0.04	**0.07**
Concrete block, unpainted	0.36	0.44	0.51	0.29	0.39	0.25	**0.37**
Concrete block, painted	0.10	0.05	0.06	0.07	0.09	0.08	**0.08**
Brick, unglazed, unpainted	0.03	0.03	0.03	0.04	0.05	0.07	**0.04**
Brick, unglazed, painted	0.01	0.01	0.02	0.02	0.02	0.03	**0.02**
Floors							
Concrete or terrazzo	0.01	0.01	0.02	0.02	0.02	0.02	**0.02**
Linoleum, vinyl on concrete	0.02	0.03	0.03	0.03	0.03	0.02	**0.03**
Floors, wooden	0.15	0.11	0.10	0.07	0.06	0.07	**0.09**
Ceilings and insulations							
Glass-fiber roof fabric	0.65	0.71	0.82	0.86	0.76	0.62	**0.74**
Fiberglass tile, 3/4″	0.74	0.89	0.67	0.89	0.95	1.07	**0.87**
Fiberglass insulation board , 3lb/ft^3,2″ thick	0.22	0.82	1.21	1.10	1.02	1.05	**0.90**

Table 5-16: Noise reduction coefficients of common building materials

Adapted from (Echeverria et al., 2019; M. Long, 2014)

[48] Building materials which have open pores with continuous channels prevail better sound-absorbing, because of the multiple reactions between the sound wave and the walls of the pores (more sound energy will be converted into heat energy).
[49] Noise reduction Coefficient (NRC) of materials should be analysed in wide-range frequencies because external sources have different frequency emissions.
[50] The most applicable sound absorbing products employed in the building industry are made out of glass-fibre or mineral-fibre materials.

Furthermore, one of the most common mistakes is to consider a porous sound-absorbing material as sound-insulating material in reducing sound transmission from one zone to another. Sound insulating materials is based on the block or stop sound energy from travelling to adjacent spaces and not on dissipating it as in the case of absorption (absorb echoes). Thus, heavy and dense materials such as gypsum board and concrete block are used to block sound, while softer porous materials like fibreglass and stone wool perform as sound absorbers (Arenas & Crocker, 2010). The sound insulation capacity of building materials is signified by the sound reduction index (R), which is also called sound transmission loss (STL) and is expressed in decibels. However, the sound insulation can be optimized for a given maximal weight of the construction by using multi-layer combinations of materials instead of a single homogeneous layer (more detailed can be seen in chapter five).

To sum up, being in an environment with inadequate acoustics can be extremely displeasing and directly impacts the occupants. Therefore, it is necessary to select an acoustically appropriate material to create an environment with better sound effects. See **Figure 5-25**

Perfectly reflective ← → Perfectly absorptive

Points	0	2	4	6	8	10
Noise Reduction Coefficients (NRC)	<0.05	≥0.05 and < 0.10	≥0.10 and <0.15	≥0.15 and <0.20	≥0.20 and <0.25	≥0.25

>0.20 =sound-absorbing material

Figure 5-25: A scoring scale for ranking building materials based on their sound absorption coefficients

To conclude this part, a health and well-being index has been created to score building materials based on the percentages of chemical hazards, embodied carbon, moisture content, fire resistance performance, visual comfort and acoustic comfort associated with their use (See **Figure 5-26**). The health and well-being index can be expressed by the following equation:

$$HWI = \sum RLI + MCI + FRPI + ECI + VTCI + ACI \quad (24)$$

Where: ***HWI***= Health and well-being Index, ***RLI***= Red List Index, ***MCI***= Moisture content Index, ***FRPI*** = Fire Resistance Performance Index, ***ECI***= Embodied Carbon Index, ***VTCI***= Visual and Thermal Comfort Index, and ***ACI***= Acoustic Comfort Index.

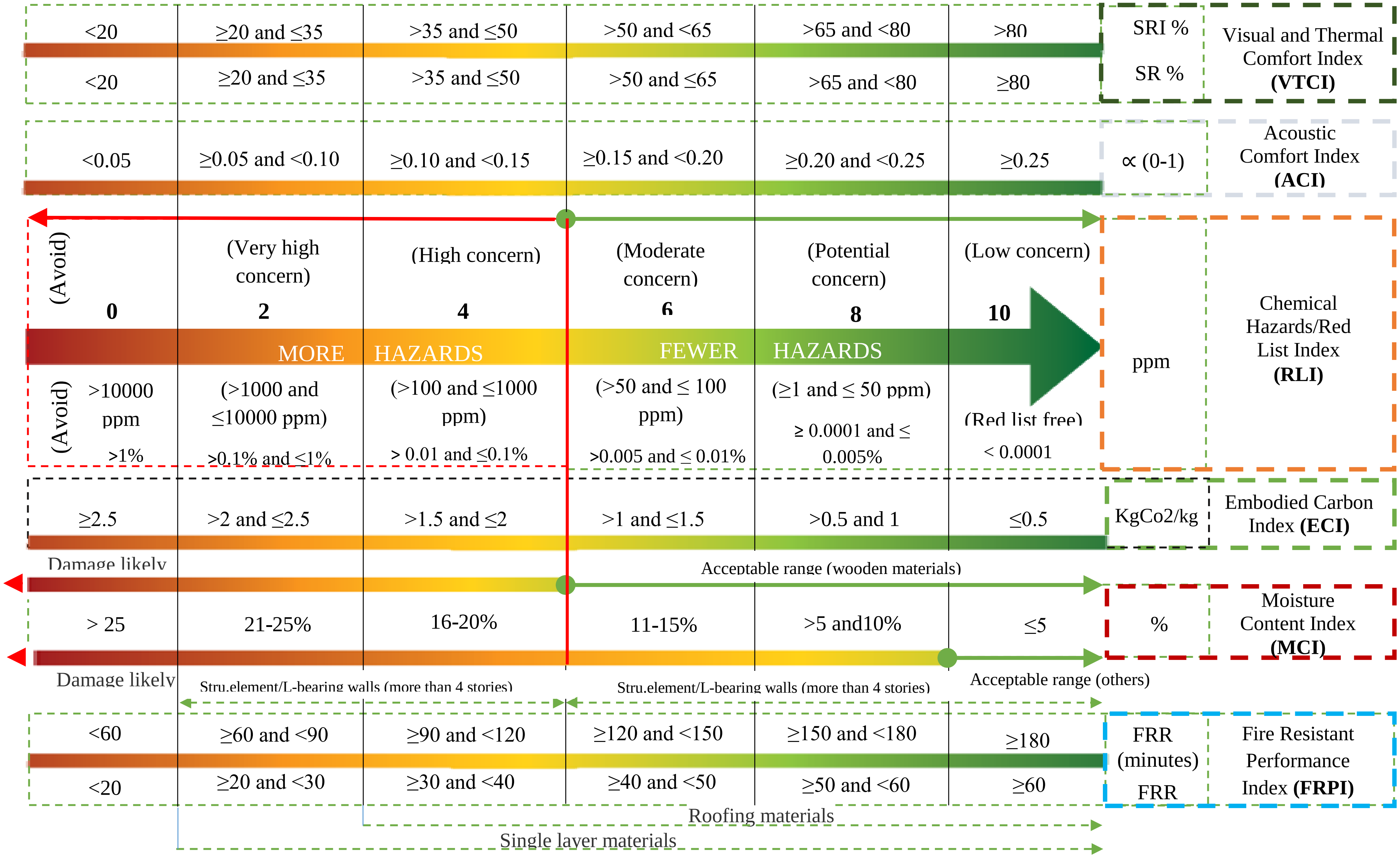


Figure 5-26: Health and Well-being Sustainability Index

5.3.4 Energy Efficiency (EE)

Energy efficiency is a multidisciplinary concept that is represented in various fields including energy and engineering and it has been used globally as an important energy policy strategy to reduce energy consumption and greenhouse gas emissions (D'Agostino, Parker, & Melià, 2019). The concerns on energy saving and CO_2 emissions reduction are implemented in the last century to be focused on using building materials with low embodied energy and better thermo-physical properties (Jeanjean, Olives, & Py, 2013; Kyriakidis, Michael, Illampas, Charmpis, & Ioannou, 2019). Moreover, Energy efficiency and energy conservation are often used interchangeably, even though they are representing different views. Energy efficiency can be defined as using less energy to generate the same amount of services or useful output, while energy conservation emphasises how much energy is consumed (Dunlop, 2019).

Buildings use approximately 48% of global energy in their construction and operation as embodied and operating energy (Dixit, 2019). Reducing embodied energy is becoming increasingly relevant, as the utilization of big quantities of raw materials in the construction industry leads to higher energy consumption in the building production stage. Further, there might be a trade-off between energy efficiency and embodied energy, as some energy-efficient buildings show an increasing amount of energy-intensive materials (Schwarz, Nakhle, & Knoeri, 2019).

The selection of materials with higher embodied-energy can lead to an increase in the level of energy consumption throughout the building's lifecycle. Therefore, the employment of low-embodied materials is considered an important approach to creating energy-efficient buildings. In addition, employing materials with good thermal properties is very important for optimal design and material selection to create energy-efficient buildings (Cobîrzan et al., 2016). Thermal conductivity, specific heat capacity, and density are the three thermo-physical properties that strongly influence the material's energy performance (Mohammad & Shea, 2013).

5.3.4.1 Embodied Energy (EE)

The extract, manufacture, transport and installation of building materials require a large quantity of energy termed embodied energy. The value for embodied energy is not the same as the value for embodied carbon (High embodied energy does not necessarily mean high embodied carbon) (Sayigh, Miller, & Ip, 2013).

Using low energy materials stores the initial energy as well as the recurring embodied energy over the building's lifespan. Undoubtedly, most natural materials such as wood and natural stone, have lower embodied energy than conventional building materials manufactured using excess processing. The total embodied-energy content for different building materials and components must be evaluated and thus compare to select the best option among alternatives. The method of estimating embodied energy is multifaceted and includes many sources of data.

Embodied energy is calculated as the quantity of non-renewable energy per unit of building material, component or system. It is stated in megajoules (MJ) or gigajoules (GJ) or area (m^2). The applied equation for estimating the initial embodied energy content of building material is given as follows:

$$\boldsymbol{E}_{\text{emb, initial, i}} = \boldsymbol{E}_{\text{xtraction, i}} + \boldsymbol{M}_{\text{anufacture, i}} \quad (25)$$

$$\boldsymbol{E}_{\text{emb, initial}} = \sum_{1}^{i} \alpha i \; mi \quad (26)$$

where $\boldsymbol{E}_{\text{emb, initial, i}}$ is the initial embodied energy of the *i*th type of building material (in MJ); $\boldsymbol{E}_{\text{emb, initial}}$ is the initial embodied energy of the whole building (in MJ); $\boldsymbol{\alpha i}$ is the embodied energy intensity factor for the *i*th type of building material (in MJ/kg), and $\boldsymbol{mi}$ is the mass of the *i*th type of building material (in kg).

On the other hand, the amount of materials used has a significant role in the total embodied energy of the building, for instance, materials with the lowest embodied energy (such as concrete, brick and timber) are usually employed in large quantities. While materials with high embodied energy level (such as stainless steel and aluminium) are often used in many small quantities. Consequently, the highest amount of embodied energy in a building can be from either high or low embodied energy materials.

According to Moncaster, Rasmussen, Malmqvist, Houlihan Wiberg, and Birgisdottir (2019), concrete and steel are often used in the main, sub and super-structure parts of the building; thus they do not need replacement over the building's lifetime, and for this reason, their relative proportion of the life cycle embodied impacts will reduce as the building life span increases. Nevertheless, it should be noted that the approach used in this research to compare the embodied energy of materials does not take into account the amounts of material required to complete a specific task, rather than a simple direct comparison of materials in a specific system such as floor, wall or roof assembly (Woodard & Milner, 2016).

The Inventory of Carbon and Energy (ICE) report from the University of Bath [51]summarizes the embodied-energy and embodied carbon values for most construction materials. **Table 5-17** shows the embodied energy intensities of different building materials.

Type of building material	Embodied energy intensities (MJ/kg)
Aluminium	155.0–227.0
Bitumen and asphalt	2.6–44.1
Bricks and blocks	0.9–4.6
Concrete	0.50–1.6
Galvanized steel	35.8–39
Glass	15.0–18.0
Stone, gravel and aggregate	0.3–1.0
Purified fly ash (PFA)	<0.1
Paint	20.0–81.5
Plaster, render and screed	1.4–1.8
Plastic, rubber and polymer	67.5–116.0
Plywood	8.5–15.0
Precast concrete element	2.0
Reinforcing bar and structural steel	9.9–35.0
Stainless steel	51.5–56.7
Thermal and acoustic insulation	3.0–45.0
Ceramic and tile	0.8–11.1

Table 5-17: Embodied energy coefficients of key construction materials

Extracted from (Baird, Alcorn, & Haslam, 1997; Chau et al., 2015; Huberman & Pearlmutter, 2008; Kofoworola & Gheewala, 2009; University of Bath, 2011)

Embodied energy is the front-end component of the lifecycle impact of a building and it is the portion that can never be changed. Embodied energy levels differ significantly with different construction types (by a factor of up to ten). As a result, figures estimated for embodied energy have wide guidelines. Therefore, it is essential to make informed choices based on a broad range to determine which building materials have the highest embodied energy and where there are alternatives to replace them (As shown in **Figure 5-27**). For selecting the best alternative and for providing fast and reliable information, embodied energy values produced by a single source using a consistent methodology and base data are often applied.

[51] This is the most popular and most widely used emission factors dataset developed by the Sustainable Energy Research Team (SERT) at the University of Bath (Hammond& Jones, 2008). The current version, ICE V2.0, was developed in 2011. This inventory surveyed peer-reviewed articles from around the world on the embodied carbon and energy of construction materials and reports the average values found from these sources.

Points	0	2	4	6	8	10
Embodied Energy Intensity (MJ/kg)	≥50	39-49	28-38	17-27	6-16	≤5

Figure 5-27: A point scale for ranking building materials based on their embodied energy intensity

The above-proposed model can be used to compare materials on a simple product-to-product basis at an early design stage when the information on materials quantities is limited.

5.3.4.2 Thermal Conductivity

Thermal conductivity is a thermo-physical measure of how much heat is transferred through a material substance by conduction (the quantity of heat transmitted through the material in unit time) (Khoukhi, 2018). Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity. It is often termed the (k) value and it is not dependent on the thickness of the materials in question (the lower the k value, the better the insulator). In the International System of Units (SI), thermal conductivity is measured in watts per meter kelvin (W/m·K). For example, a material with a k value of 1 w/m.k, will transmit heat at a rate of 1 watt for every degree of a temperature difference between opposite faces of a cube with 1-meter sides.

K-values can be used to compare the thermal conductivities of different materials. Typically it is a fundamental property in assessing the potential for heat transfer between the inside and outside of a building. In the construction industry, the use of low thermal conductivity materials is regarded as one of the most effective means of energy conservation in buildings. For instance, metals typically have high thermal conductivity and are very efficient at conducting heat, while the opposite is true for insulating materials like rock wool. Furthermore, thermal conductivity is affected by the material's chemical composition and molecular structure, porosity, temperature and humidity, and the direction of the heat current (P. S. Liu, Chen, Liu, & Chen, 2014).

Furthermore, the reciprocal of thermal conductivity is called thermal resistivity (R-value). It is used to determine the thermal resistance of a specific thickness of a material and can be calculated by dividing the thickness of the materials (in meters) by its k-value, and can be expressed in m^2k/w. Obviously, the overall R-value of a multi-layered element can be calculated by adding the R-values of its component materials (the higher the R-value, the greater the insulating effectiveness).

On the other hand, the heat transfer coefficient (U-value) is used to determine the thermal conductivity of an entire building assembly, including the internal and external materials; these might include walls, floors and roofs. In other words, a U-value is applied to determine how good or how poorly an assembly transfers heat from the inside to the outside. It has been used in numerous projects to improve the indoor thermal comfort and the energy performance of the entire building. The U-value is a very effective method of predicting the composite behaviour of an entire assembly (multi-layers) rather than relying on the properties of single materials (the lower the U-value, the slower the heat transfer through the building component). The U-value is measured in W/m^2K.

The following information is needed to calculate the U-value for each layer:

I. Thermal conductivity (W/m.K).

II. Material thickness (meters).

III. R-value for each layer (dividing the thickness (meters) by the thermal conductivity).

IV. The total U-value for the assembly can be calculated by adding the R-value of each element plus the internal and external resistance R-values. Divide the total R-value into 1 (U=1/R). (See **Table 5-18**)

Material	Thickness (m)	Thermal Conductivity (K-value) w/m.k	Thermal Resistivity (R-value) = thickness ÷ conductivity (m^2k/w)
Outside Surface	-	-	0.040
Clay bricks	0.100	0.77	0.130
Glasswool	0.100	0.04	2.500
Concrete blocks	0.100	1.13	0.090
Plaster	0.013	0.50	0.026
Inside Surface	-	-	0.130
Total			2.916
U-value =		1÷2.916	**0.343 w/m²****.k**

Table 5-18**:** Example of U-value calculations of a building component

Furthermore, regulations to control the thermal performance of building envelopes have been established in many countries worldwide. These standards specified the minimum and the maximum acceptable limit of the U-value of building envelopes (Natephra, Yabuki, & Fukuda, 2018). Over the last decade, the minimum required performance level of a building envelope has been tightened considerably to promote the spread of energy-efficient buildings (Choi & Ko, 2019). However, different standards cover different climatic zones. A U-value is typically a low number (in various climates) because it is a rating of how much heat lost or gained through a building's assemblies. Therefore, the lower the U-Value, the more energy-efficient the assembly in question will be. A more detailed discussion regarding the optimal values of building envelopes can be found in chapter six.

5.3.4.3 Specific Heat Capacity

Specific heat capacity is an important property for building materials that are used for the thermal evaluation of building constructions. It refers to the amount of heat needed to raise the temperature of 1kg of the material by 1K (or by 1°C) (the capacity of the material to store heat for every kilogram of mass). Typically, a good insulator material has a higher specific heat capacity[52] because it takes time to absorb more heat before it heats up to transfer the heat. Recently, new buildings use modern lightweight materials and technologies which reduced the overall thermal mass of the constructions. The lack of thermal mass materials causes problems with overheating and thermal discomfort in today's buildings. Nevertheless, the design of building materials should be optimized concerning their thermal mass and specific heat properties. Ideal materials for thermal mass require a combination of properties such as a high specific heat capacity, a high density, and moderate thermal conductivity. Specific heat capacity is measured in J/kg.K.

5.3.4.4 Density

The density refers to the mass or weight per unit volume of a material and is measured in kg/m^3. It represents the degree of compactness of a material. A high-density material maximizes the overall weight and is an aspect of low thermal diffusivity and high thermal mass. The materials with a high density generally have a low specific heat capacity and those with high specific heat capacity often have a low density (L. Long & Ye, 2015). Generally, low-density building materials occupy more volume than higher dense materials. Density is defined as the ratio of mass to volume.

$$\mathbf{p = m/v} \quad (27)$$

Where **p** is the density, **m** is the mass and **v** is the volume.

[52] Water has a specific heat capacity of 4.18 J (or 1 calorie/gram °C) which is a much higher value than that of most other substances. This value makes water outstandingly good at controlling temperature.

Listed below is a table of common building materials, their heat capacity, density, and specific heat capacity. More materials parameters can be seen in Appendix F.

Building Materials	**Thermal Conductivity k (W/(m.K))**	**Specific Heat Capacity C_p (J/kgK)**	**Density D (kg/m^3)**
Aluminum	230	880	2700
Brickwork (outer leaf)	0.84	800	1700
Aggregate (sand, gravel or stone)	1.3	920	2240
Cement Mortar (moist)	1.5	840	1900
Cement Plaster	0.72	840	1720
Gypsum Plasterboard	0.16	840	800
Ceramic Tiles	1.2	850	2000
Hollow concrete block (heavyweight,300mm)	1.35	840	1220
Concrete (dense)	1.7	840	2200
Steel (stainless 5% Ni)	29	480	7850
Rock wool	0.037	710	23
Granite	3.49	840	2880
White Marble	2	880	2500
Hardboard (Timber)	0.08	2000	600
Vinyl floor covering	0.19	1470	1200
Expanded polyurethane	0.023	1590	24

Table 5-19: Typical thermal conductivity, specific heat capacity and density of common building materials

The consideration of these properties during the material selection stage is necessary for modelling and managing heat, whether the component of interest is used to insulate, conduct, or simply withstand temperature changes. These properties have a direct impact on the energy performance and storage capacity of the material and building. Nevertheless, other properties such as thermal transmittance, thermal resistance, thermal diffusivity[53], thermal effusivity[54], and thermal mass can be determined from the basic properties. According to the nature of the human thermal problem in a particular location, the human settlement environment on earth can be categorized into four basic types (hot-dry, hot-humid, temperate, and cold climate). In hot-dry climates, building materials are primarily selected to prevent external heat gain or internal heat loss since there is a wide

[53] Thermal diffusivity measures the rate of transfer of heat of a material from the hot end to the cold end. Thermal diffusivity a associates the thermal conductivity k, the specific heat C and the density ρ of the material under the definition $a = k/\rho C$.

[54] Thermal effusivity, thermal inertia or thermal responsivity characterizes the ability of the material to exchange thermal energy with its surroundings. The thermal effusivity (e) is defined as the square root of the product of the material's thermal conductivity k and its volumetric heat capacity ρC. Thermal effusivity is given by the following equation: $e = \sqrt{(k\ \rho C.)}$

difference between indoor and outdoor temperatures. Therefore, materials with good thermal mass properties are preferable in these climates to minimize energy consumption and to maintain the thermal comfort of the buildings. In cold climates, the main concern is to minimize any heat loss, therefore the ability of building material to provide a good thermal insulation capacity is of prime concern. Also, materials with good capacitive insulation can be beneficial in continuously occupied buildings. In temperate climates, materials with both high thermal insulation and thermal mass properties are preferable (the night-time temperatures are too low even in the summer). In hot-humid climates, materials are mainly selected for solving the sun shading and heat insulation. Therefore, materials with good thermal insulation properties perform better to maintain an adequate indoor environment and providing energy-efficient buildings. In temperate climates (mild to warm summers and cool to cold winters), materials with moderate heat storage capacity (thermal mass) and sufficient thermal insulation properties are suited for this climate.

As a general rule, materials with low thermal conductivity, high specific heat capacity, and low-density values are considered as good thermal insulators, while materials with high density, high specific heat capacity and moderate thermal conductivity are capable to provide high thermal mass in buildings. **Figure 5-28** shows a ranking scale for selecting building materials based on their thermo-physical performance in different climates.

For buildings located in hot-dry climates						
Points	**0**	**2**	**4**	**6**	**8**	**10**
Thermal conductivity (W/ m.K)	>5.5	>4.5 and ≤5.5	>3.5 and ≤4.5	>2.5 and ≤3.5	>1.5 and ≤2.5	≤1.5
Specific Heat Capacity J/(kg.K)	<100	≥100 and <500	≥500 and <1000	≥1000 and <1500	≥1500 and <2000	≥2000
Density (kg / m3)	<500	≥500 and <1000	≥1000 and <1500	≥1500and <2000	≥2000 and <2500	≥2500
For buildings located in hot-humid climates						
Points	**0**	**2**	**4**	**6**	**8**	**10**
Thermal conductivity (W/ m.K)	>0.45	>0.35 and ≤0.45	>0.25 and ≤0.35	>0.15 and ≤0.25	>0.05 and ≤0.15	≤0.05
Specific Heat Capacity J/(kg.K)	<100	≥100 and <500	≥500 and <1000	≥1000 and <1500	≥1500 and <2000	≥2000
Density (kg / m3)	≥2500	≥2000 and <2500	≥1500and <2000	≥1000 and <1500	≥500 and <1000	<500
For buildings located in cold climates/ temperate climates						
Points	**0**	**2**	**4**	**6**	**8**	**10**
Thermal conductivity (W/ m.K)	>0.45	>0.35 and ≤0.45	>0.25 and ≤0.35	>0.15 and ≤0.25	>0.05 and ≤0.15	≤0.05
Specific Heat Capacity J/(kg.K)	<100	≥100 and <500	≥500 and <1000	≥1000 and <1500	≥1500 and <2000	≥2000
Density (kg / m3)	<500	≥500 and <1000	≥1000 and <1500	≥1500and <2000	≥2000 and <2500	≥2500

Figure 5-28: A scoring scale for selecting building materials based on their thermo-physical performance

In conclusion, the selection of given building material can have multiple effects on the energy consumption over the different stages of a building's life cycle, in many cases, these effects can be inconsistent since properties such as high thermal conductivity of material may return relative savings in operational energy together with higher embodied-energy intensities. Therefore, the balance between these factors is especially significant when selecting energy-efficient building materials. The final energy efficiency index can be obtained by scoring building materials based on both embodied energy intensity and thermo-physical properties as shown in **Figure 5-29**. The simplistic index can be used by construction stakeholders as an indicator for measuring building materials to select the best energy-efficient solutions.

Points	**0**	**2**	**4**	**6**	**8**	**10**
Embodied Energy Intensity (MJ/kg)	≥50	39-49	28-38	17-27	6-16	≤5
For buildings located in hot-dry climates						
Points	**0**	**2**	**4**	**6**	**8**	**10**
Thermal conductivity (W/ m.K)	>5.5	>4.5 and ≤5.5	>3.5 and ≤4.5	>2.5 and ≤3.5	>1.5 and ≤2.5	≤1.5
Specific Heat Capacity J/(kg.K)	<100	≥100 and <500	≥500 and <1000	≥1000 and <1500	≥1500 and <2000	≥2000
Density (kg / m3)	<500	≥500 and <1000	≥1000 and <1500	≥1500and <2000	≥2000 and <2500	≥2500
For buildings located in hot-humid climates						
Points	**0**	**2**	**4**	**6**	**8**	**10**
Thermal conductivity (W/ m.K)	>0.45	>0.35 and ≤0.45	>0.25 and ≤0.35	>0.15 and ≤0.25	>0.05 and ≤0.15	≤0.05
Specific Heat Capacity J/(kg.K)	<100	≥100 and <500	≥500 and <1000	≥1000 and <1500	≥1500 and <2000	≥2000
Density (kg / m3)	≥2500	≥2000 and <2500	≥1500and <2000	≥1000 and <1500	≥500 and <1000	<500
For buildings located in cold climates/ temperate climates						
Points	**0**	**2**	**4**	**6**	**8**	**10**
Thermal conductivity (W/ m.K)	>0.45	>0.35 and ≤0.45	>0.25 and ≤0.35	>0.15 and ≤0.25	>0.05 and ≤0.15	≤0.05
Specific Heat Capacity J/(kg.K)	<100	≥100 and <500	≥500 and <1000	≥1000 and <1500	≥1500 and <2000	≥2000
Density (kg / m3)	<500	≥500 and <1000	≥1000 and <1500	≥1500and <2000	≥2000 and <2500	≥2500

Figure 5-29: Energy efficiency Index

The thermophysical properties might be examined to check the suitability of solid building materials to achieve energy efficiency in buildings, however, if glazing materials are selected[55], then properties like thermal transmittance (U-value or U-factor) and solar heat gain coefficient SHGC[56] should be investigated for energy reduction. In general, glazing materials with high SHGC and low U-value is appropriate for use in cold climates

[55] The main advantage derived from good selection of glazing materials is a reduction in energy demand by buildings, including heating, cooling and lighting energy.
[56] Also known as the total solar energy transmittance (TSET)

and temperate climates, while glazing with low SHGC and low U-value[57] is suited to be used in hot-dry climates and hot-humid climates (more details in Chapter five).

5.3.5 Water Efficiency (WE)

Due to rapid urbanization and economic growth, water scarcity[58] draws worldwide attention in recent years. According to S. Chen, Tan, and Liu (2019), about 75% of the world's population may face the scarcity of available freshwater by 2050. Water resources are of fundamental importance as the most essential matters for human life, economy, and society (Y. Li & Han, 2018). Also, two of the seventeen United Nation's Sustainable Development Goals (SDGs) directly address the significance of water (Al-Qawasmi, Asif, El Fattah, & Babsail, 2019).

Water is one of the most vital natural resources and is expansively used in the building sector. The availability and quality of water are crucial throughout the building's lifetime. Globally, the construction and building sectors entail 12% of water consumption (Alawneh et al., 2018). However, several studies have been conducted to investigate water consumption by buildings. According to a report from the United Nations environment program: the building sector was responsible for approximately 30% of global freshwater consumption (Meng et al., 2014). Therefore, assessing the efficiency of water-energy consumption is an urgent issue for achieving resource conservation and sustainability in the construction industry.

The evaluation of water consumption in the operation and maintenance stages of the buildings (operational water) is widely analyzed, thus more studies are needed to estimating the water embodied in the construction process and material contribution (M. Y. Han et al., 2016). Previous studies showed that the indirect water consumed during the construction process from the extraction (mining), production, manufacturing, and delivery, is of great significance for water conservation (R. H. Crawford & Pullen, 2011). This is known as indirect or embodied water.

5.3.5.1 Embodied Water (EW)

Water is required in direct construction activities (e.g. water consumed by labours, water used for dust repression, and water wasted for washing of hard surfaces and equipment), and likewise for the production of construction materials as embodied water.

[57] In any climate where the average outdoor temperature is constantly above or below the human comfort level, a low U-value is an advantage.

[58] The expected growth in the world population, the rise in average temperature (Global Warming), and the pollution increase of the water-supply infrastructures, all can alter natural water resources and cause freshwater scarcity.

Construction activities and mining require a huge volume of water for everyday operation. Water is the essential ingredient to produce many building materials, for instance, concrete is the single most widely used material in the world and water is the basic ingredient to produce it (cement and concrete). Also, water is used in the manufacturing process of steel, brick, cement, aluminium, glass, and carpet (M. M. Rahman, Rahman, Haque, & Rahman, 2019).

Embodied water can be defined as the water needed to create and deliver a product or material through all stages of manufacturing. According to Choudhuri and Roy (2015), water embodied in the materials of construction is much more significant than the actual water use during the construction process. **Table 5-20** shows the embodied water coefficient (given in kiloliter per unit) of the main building materials.

Material	**Unit**	**Water intensity (KL/Unit)**	**Material**	**Unit**	**Water intensity (KL/Unit)**
Aluminum	t	1084.00	Membrane (1mm)	m^2	1.4
Aluminum, reflective foil	m^2	0.59	Oil-based paint	m^2	0.22
Clay Bricks (110mm)	m^2	0.67	Plasterboard (10mm)	m^2	0.63
Carpet, nylon	m^2	1.58	Plastic (PVC)	t	366.36
Clear float glasses (4mm)	m^2	3.42	Steel, stainless	t	649.55
Concrete (20 MPa)	m^3	10.98	Steel, structural	t	98064
Concrete roof tiles (20mm)	m^2	0.91	Tiles, ceramic	m^2	1.12
Concrete block, hollow (200mm)	m^2	2.67	Precast	m^3	4.44
Fiber cement sheet (4.5mm)	m^2	0.75	Timber, hardboard	m^3	16.28
Fiberglass insulation (R2.0)	m^2	0.38	Timber, softwood	m^3	20.14
Fiberglass insulation (R4.0)	m^2	0.69	Toughened glass (6mm)	m^2	8.24
MDF/particleboard	m^3	85.59	Water-based paint	m^2	0.21
Cement	t	29.91	Vinyl flooring (2mm)	m^2	1.72

Table 5-20: Embodied water coefficient of main building materials

Extracted from (R. Crawford, 2017; R. H. Crawford & Pullen, 2011)

Some materials (such as aluminium[59], stainless steel, glass fibre and PVC) consume a lot of water to produce and have a large water footprint. The concept of embodied-water and water footprint is not as popular as the concept of embodied-energy and energy footprint. The embodied water is obviously overlooked and discounted. Yet, with the growing scarcity of freshwater, embodied-water will become an important issue in sustainable practice. This also requires that the embodied water intensity of all building materials should be known[60]. The embodied water can be calculated by the following equation:

$$\mathbf{EWemb,}_{\text{initial}} = \sum_{m=1}^{M} (\boldsymbol{WCm} \times \boldsymbol{Qm}) \ldots\ldots\ldots\ldots \quad (28)$$

Where **EWemb**, $_{\text{initial,}}$ is the initial embodied water; $\boldsymbol{WCm}$ is the embodied water coefficient of material, m; $\boldsymbol{Qm}$ is the quantity of material.

On the other hand, the embodied-water intensity required to manufacture the individual construction materials can be used to influence decision-makers to select water-efficient materials in addition to minimizing overall water consumption in buildings.

Figure 5-30 shows a scaling system based on points to rank building materials based on their embodied-water intensity.

Points	0	2	4	6	8	10
Embodied Water Intensity (KL/Unit)	>20	16-20	11-15	6-10	1-5	<1

Figure 5-30: A point scale for ranking building materials based on their embodied water intensity

5.4 Chapter Summary

In the early stages of building design, the benefits of incorporating sustainability principles in guiding project decisions and design iterations have been well highlighted. The process of architectural design begins by defining the construction technology and the selection of construction materials. One area of challenge is the development of a

[59] Significant water resources are required for the production of aluminum. For instance, water is used to produce the steam needed in the Bayer's process; in the preparation of aqueous caustic soda, flocculants and lime; to wash the ore, residues and recycled caustic and for dust mitigation.

[60] The direct water can be easily calculated because it is a single source of consumption, while the indirect water (embodied water) is harder to specify because of the various sources of consumption that might be involved.

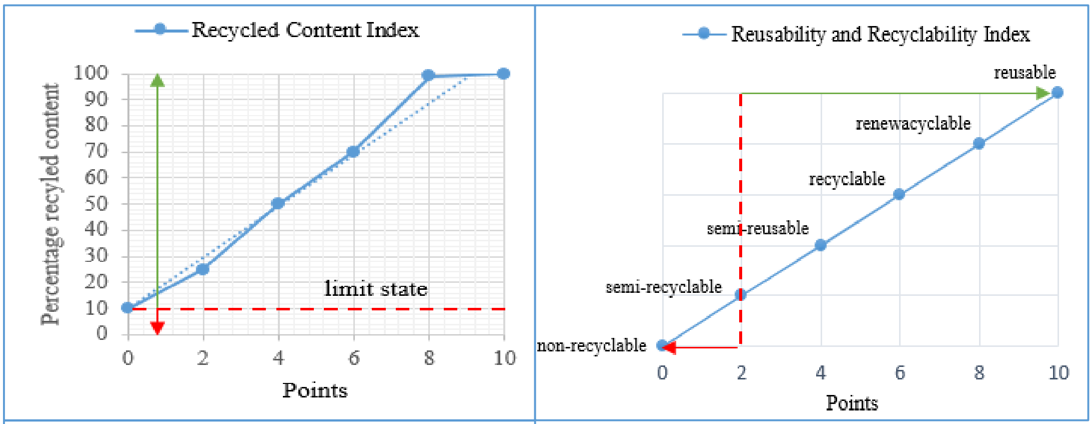
multi-criteria tool to guide the designers in making the optimum material selection decisions. The selection of green building materials is a complex decision-making process requiring the needs of a range of stakeholders such as designers, architects, clients, contractors, and engineers. Therefore, it needs group decision-making in which multiple individuals collectively analyze the issues under discussion, establish assessment criteria (which usually come into conflict with each other), conduct measurement and make the final choice from a range of alternative building materials. This process usually leads to consensus problems due to the variations in the interests, knowledge, and experiences of the engaged participants.

This chapter presented a framework and the representative conceptual model for developing a sustainability assessment method for building materials. The model is expected to provide the basic reference in developing a sustainability index for materials selection to facilitate rational decision making and realizing sustainable development goals. The framework is initiated on the concepts of life cycle assessment and it has been developed based on a holistic sustainable assessment criterion set to assist in the selection of green building materials for a building project; including economic, environmental, social, and technical criteria.

The proposed model does not require the complex and subjective pair-wise comparison to determine the weights of the selection criteria, which mitigates such kind of subjective errors. Though, the framework enables direct comparison based on various criteria between available alternatives. Moreover, the adopted methodology can be employed for the selection of green building material alternatives in different locations worldwide.

Building materials cannot be defined as green just by looking at whether they are recyclable or have higher recycled content and low embodied energy and carbon. There are many factors to consider when searching for sustainable materials. The compromise between conflicting factors (criteria) is necessary. It should be pointed out that, criteria related to aesthetics and architectural expression (e.g. sight and texture) are not included in this framework because they are largely subjective and difficult to quantify.

In conclusion, the selection of building materials should be carried out paying attention to the natural resources and raw materials consumed, the provision of a high level of Indoor Environmental Quality, the materials availability and their life-cycle cost, energy and water intensity of materials; and the overall impact on the environment. **Figure 5-31** to **Figure 5-34** show the various employed criteria and their acceptable values.



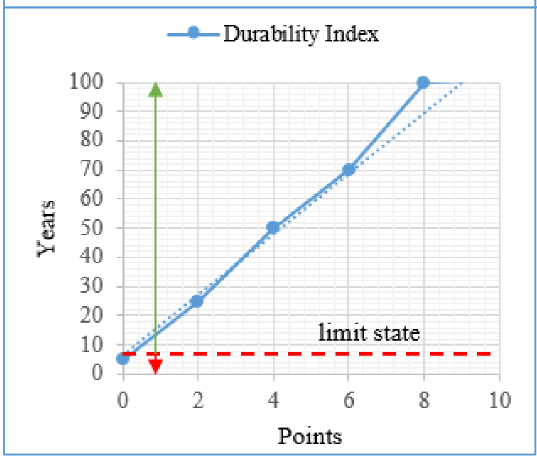


Figure 5-31: Final Resource-efficiency Index

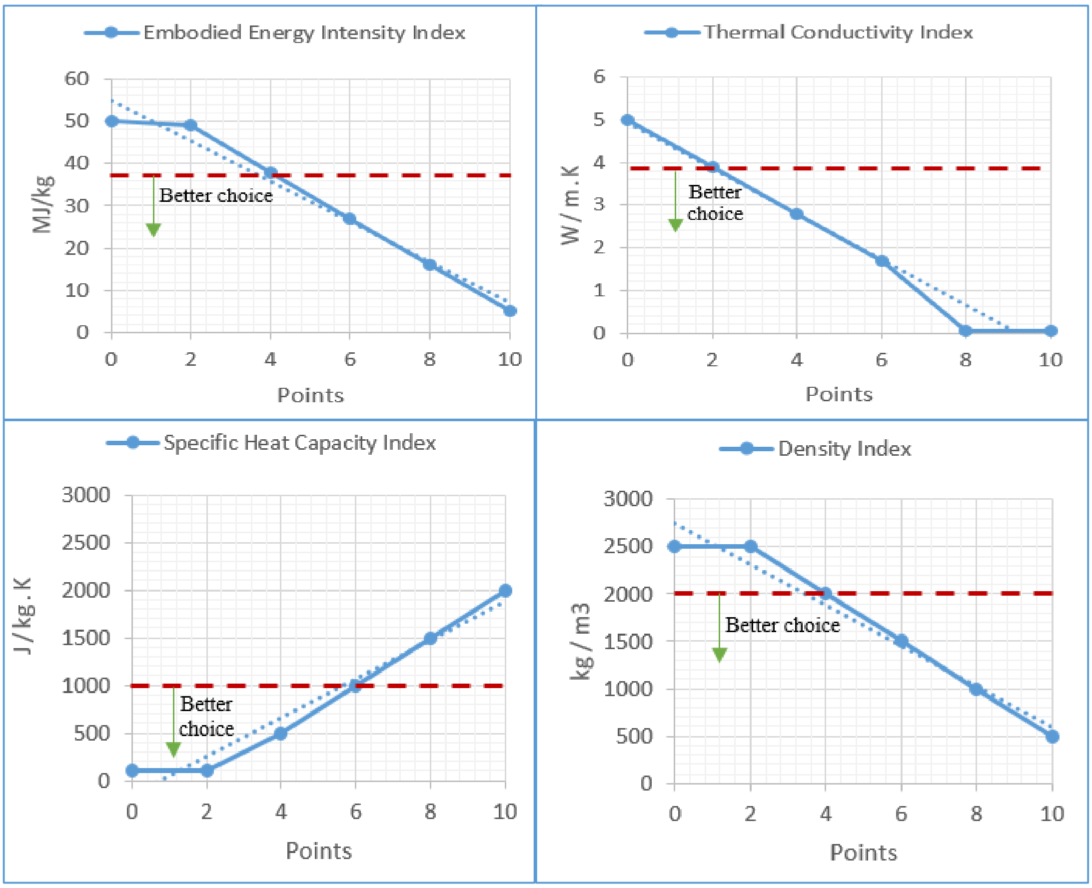


Figure 5-32: Final Energy-efficiency Index

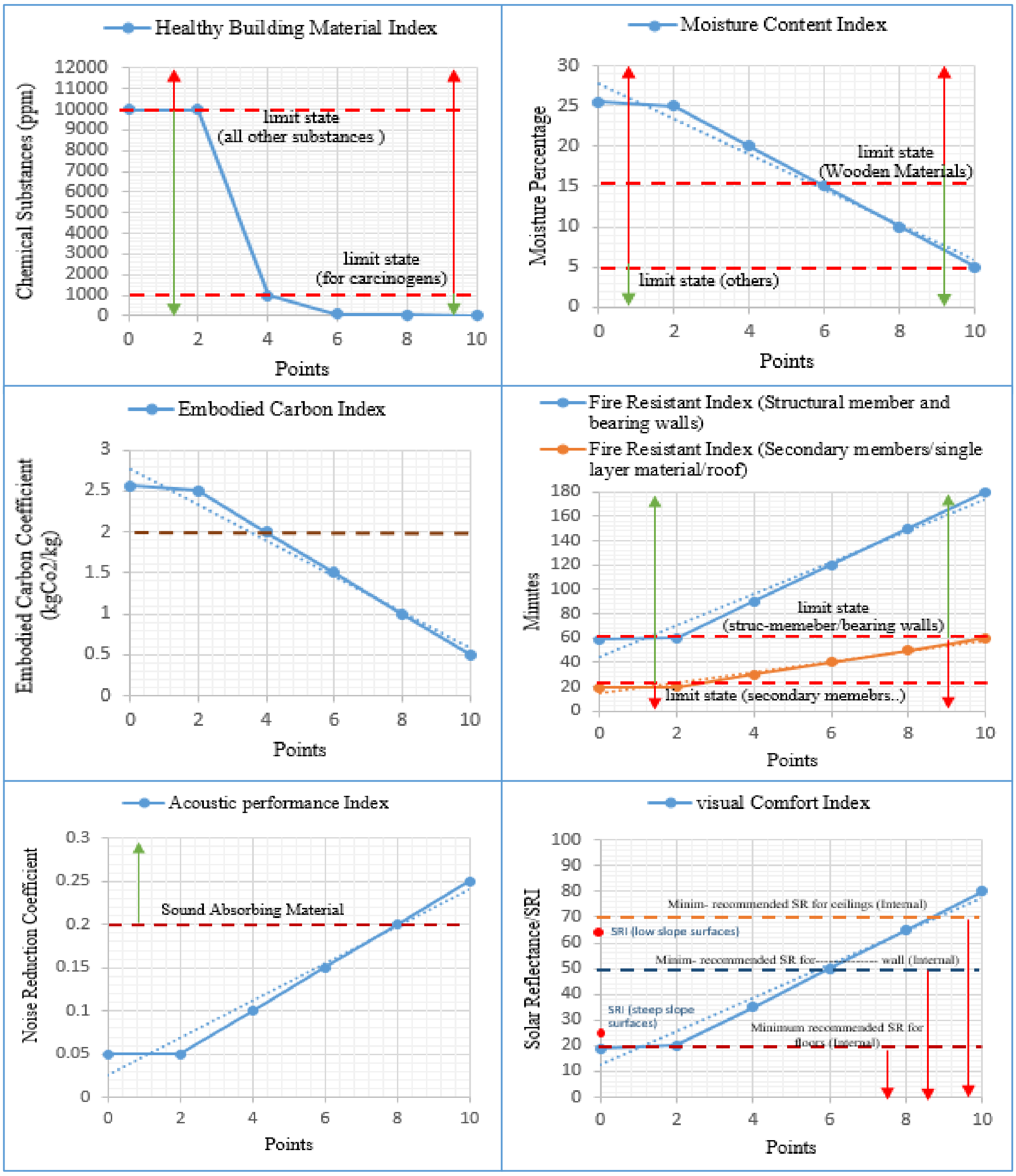


Figure 5-33: Final Health and Well-being Index

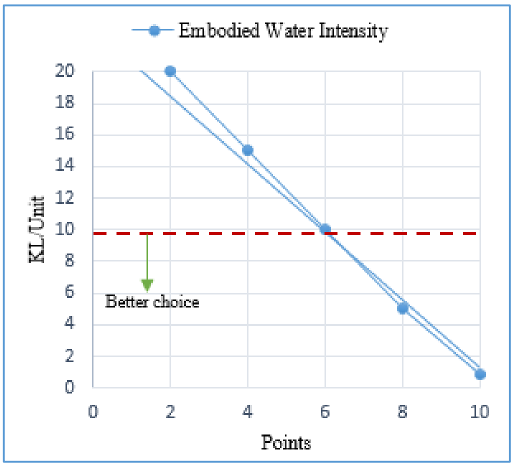


Figure 5-34: Final Water-efficiency Index

CHAPTER 6: REVIEW OF BUILDING ENVELOPE ASSEMBLIES AND MATERIALS

6. CHAPTER SIX: REVIEW OF BUILDING ENVELOPE ASSEMBLIES AND MATERIALS

6.1 Overview

The building envelope is the physical barrier between the indoor (conditioned) and the outdoor (unconditioned) environments enclosing structure. It is the dominant system in all subsystems of the building. According to Brock (2005), the building envelope is the skin of a building that is supported by the skeleton of the building structure, ensures comfortable conditions in the interior and provides security. The building envelopes have become progressively significant in the areas of research and development due to the growing awareness of environmentally sustainable building constructions. According to Straube and Burnett (2005), the basic building envelope functions can be categorized into three sub-groups as follows:

• Support functions (to withstand and transfer structural loads).

• Control functions (moderate all the loads/the control of mass and energy flows).

• Finish functions (to meet human needs in the interior and exterior environments (visual, aesthetic, wear and tear).

The following questions should be addressed at the early design stage of building envelopes to mitigate any kind of contrasting points and to ensure that the performance objectives will be fully satisfied:

I. What is the practical purpose of the building envelope (function)?

II. What does the building envelope look like (form)?

III. What is the elements/components of the building envelope and how are these elements assembled into a whole (form)?

IV. What is the resources consumption and impacts of the building envelope (natural environment and people's health) throughout their lifespan (ecological sustainability)?

On the other hand, the selection of the type of structural system is to govern the application of the building envelopes and how these systems are related and integrated. In this regard, there are three basic types of structural systems including solid construction (building envelopes are applied or integrated into the structural elements); filigree construction (building envelopes are separated from the structural elements); and pneumatically stabilized construction (building envelopes integrated to the structural elements) (Andrea & G. H., 2005; Košir, 2019). All of the following forms of construction systems can be derived from the mixing of solid construction[61] and filigree[62] construction. Also, the Pneumatic structures can be used to create a whole structure as a unit or part of another system. However, the building envelopes should be purposely designed and selected to separate between the indoor and outdoor taking in mind the structural system and services. See **Figure 6-1**

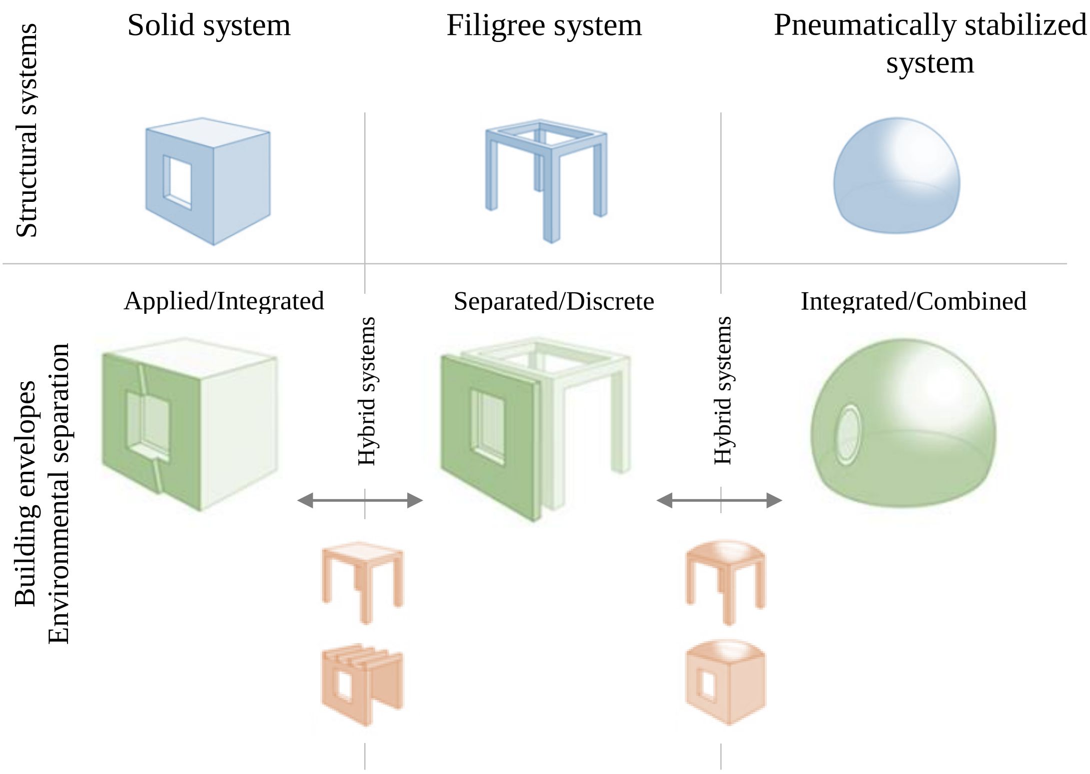


Figure 6-1: The basic three types of structural systems and their relation to the execution of environment separation of building envelopes

Adapted according to (Košir, 2019)

Historically, building envelopes were constructed using a single-layer to keep undesirable external influences from affecting the indoor environment. Such kind of construction has existed for a long period where stone, brick, rammed earth and timber have been used as both structural and building envelope materials. Furthermore, with the development of modern buildings, construction technology and demands concerning building

[61] In solid construction the erection of walls creates interior spaces directly because the loadbearing and enclosing functions are identical.

[62] The term "filigree construction" refers directly to the way in which these forms of construction are put together.

performance, more complex multi-layered building envelopes emerged to perform several environmental control functions (Schittich, 2006). Recently, the building envelope is comprised of a series of components and systems; including the exterior walls, roofs, foundations, doors and windows. Each component is a multi-layer and multi-material assembly that continues from the inside face of the innermost interior layer (e.g., the paint or plaster) to the outside face of the outermost layer (e.g., paint or roof shingles). The overall assembly is constructed from the all connecting layers. See **Figure 6-2**

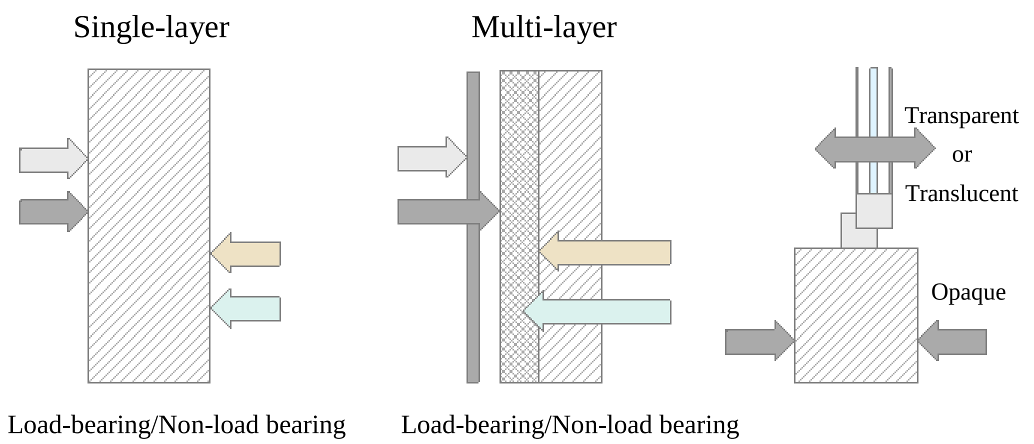


Figure 6-2: Building envelope typology

Adapted according to (Schittich, 2006)

The role of the building envelope is to keep constant humidity and temperature levels inside the building, and also protect the indoor zones from external environmental exposures such as wind, temperature, and precipitation. Consequently, the building envelopes are endlessly subjected to the loads from different energy runs to make the balance between the inside and outside (Ulrich et al., 2018) (See **Figure 6-3**). Therefore, the materials and the structure of the building envelopes must satisfy the building physics demands of heat, moisture, fire, sound and light (see **Table 6-1**). The facades and roofs have been considered as the most important building envelope components and they are discussed in the following sub-sections.

6.1.1 Building facades (walls)

Façades have a significant impact on overall building performance and they play an important role in regulating the indoor environment and the comfort level of occupants as well as energy demand of a building (Tong, Wong, Tan, & Jusuf, 2019). Historically, there are two typologies of façade envelopes; single skin facade envelope and double or multiple skin façades (Kumar & Raheja, 2016). The single skin façade is made of a single layer material (such as brick, stone, or prefabricated brick) and it has been widely used to cut the construction cost. While double or multiple skin façades are composed of two or more layers and it has been used on a larger scale since the nineties to achieve several properties that can increase building performance (Hamza, 2008). The building facades occupy a significant portion of the external envelope, thus significantly affect the functional and structural performance of the buildings.

Building façades have been considered as the most technically demanding, multidimensional and integrative components of a building (Halawa et al., 2018). According to Bonner, Wegrzynski, Papis, and Rein (2020), creating a façade is a multi-objective problem; in which improving one objective may cause a trade-off in another parameter, for example improving the moisture control of the façade may limit its ability to resist fire. The design of sustainable facades entails a team of architects, engineers and environmentalists to work in partnership towards achieving the optimum design (Halawa et al., 2018). Generally, building façades are classified into two groups, specifically opaque and transparent façades. Opaque façades are mainly constructed of solid layers of materials such as masonry, stone precast concrete panels, metal cladding, insulation, etc. Secondly, the glazed façades are primarily made of transparent or translucent glazing materials for example curtain walls or storefront facades (Ajla, 2013; Shahin, 2019).

Moreover, many parameters need to be considered when designing building façades. These include external and internal walls and materials, façade properties (ex. height, length, width, glaze type, window to wall ratio (WWR) etc.), outdoor environment and microclimatic conditions, thermal insulation of façades, and external shading (Mirrahimi et al., 2016). Among the mentioned parameters, the selection of façade's materials is considered the most important factor in constructing sustainable facades (Aksamija, 2015).

The selection of appropriate façade material from an enormous number of alternatives is a complex decision demanding a large amount of information and input from the design team (Moussavi Nadoushani et al., 2017). The selection of façade's materials must be based on many criteria including material's functionality, a competitive cost, energy efficiency, strength and stability, ease of installation, deconstruction and maintenance, resistance to chemicals, fire, moisture, noise, and so on. However, a systematic approach is needed to integrate these criteria into a practical model to facilitate the selection of appropriate facade materials and system.

Environmental/Climatic influence	**Approaches to control the indoor environment**	**Possible controlling measurements through envelope configuration and material selection**
Water (Moisture migration)	Waterproofing	Moisture content Water resistive barrier
	Drainage	Surface Water Runoff (face seal) Flashing Drain cavity (rainscreen system)
	Vapour diffusion	Vapour barrier Vented cavity Thermal insulation position
Heat (solar radiation and temperature)	Heat transmission control (opaque construction)	Surface conductivity Surface reflectivity Surface emissivity Thermal insulation Thermal mass (Thickness, density and specific heat capacity)
	Heat transmission control (glazing systems)	Glazing optical properties (Glazing transmittance, Reflectivity, emissivity….etc.) Shading devices
Light (solar radiation)	Natural lighting (visible light spectrum)	Glazing optical properties Shading devices Orientation
Air	Airtightness	Air barrier Airtight construction
	Ventilation	Fenestration Ventilation openings Ventilation systems Orientation
Sound	Sound insulation	Sound reduction index Sound absorption Geometric properties
Fire	Fire insulation	Fireproof materials Self-extinguishing materials Nontoxic materials

Table 6-1: Building envelope control layers and corresponding controlling measurements through envelope configuration and material selection

Adapted according to (Andrea & G. H., 2005; Kesik, 2016b; Košir, 2019)

6.1.2 Building Roofs

The total surface of the roofs in the urban world is estimated at nearly 380 billion m^2, while the roof surface accounts for over 20% of the total urban area (Kolokotsa, Santamouris, & Zerefos, 2013). Particularly, the roofs have a considerable effect on the total energy consumption of air-conditioned buildings, in addition to the thermal comfort of the internally non-air-conditioned buildings (Tong & Li, 2014). Building roof receives three times more solar energy than vertical facades (B. Park, Srubar, & Krarti, 2015). According to Gao et al. (2017), the heat gains from roofs for the low and mid-rise buildings constitute between 5-10% of the annual cooling energy consumption of a building and more than 40% of the cooling energy consumption of the top floor. Although roofs have a significant impact on heat gain and heat loss in buildings, they are the key drivers for ensuring sustainable development, environmental protection and promote the economic growth and human well-being of their covered buildings (Berto, Stival, & Rosato, 2018).

Furthermore, roofing materials are one of the most essential construction materials of any building. They ensure the safety and thermal comfort of the indoor spaces as well as improve the overall energy performance and reduce the negative impact of buildings on the environment. The existing building roofs have been constructed with materials that have low reflectance and poorer insulation capabilities which make them incompetent to reduce solar heat gains (summer) or heat losses (winter) in buildings. Also, it has been noted that several conventional roofing materials (such as cement asbestos fibre reinforced and coated metal sheets) have significant environmental impacts not only during manufacturing but also usage and disposal phases (U.D.G.U.C & Asela, 2014). Therefore, the selection of optimal roofing materials among alternatives is very important, and an extensive range of criteria need to be considered from an early design stage (S. Rahman, Odeyinka, Perera, & Bi, 2012).

In the previous chapter, the model of selecting individual building materials based on a set of comprehensive criteria has been introduced. Nevertheless, it is highly important to highlight the impact signified by the combination of these materials when applied for a certain construction assembly. It is more common for most people to evaluate the sustainability of the buildings by examining building components and assemblies rather than individual materials. Likewise, it is necessary to identify the suitability of the building assemblies throughout their lifetime before integrating them into the building envelope. In this regard, architects and designers must be able to control the selection of suitable materials and building assemblies employed in various projects to achieve the overall sustainable design (Huedo, Mulet, & López-Mesa, 2016). Furthermore, the selection of appropriate materials combination from an early design stage plays a critical role in the optimization of a building's life cycle performance in terms of resources efficiency, energy consumption and life cycle costs (Sierra-Pérez, Boschmonart-Rives, & Gabarrell, 2016).

Obviously, the assessment of the building assemblies used for the envelope requires a scientifically rigorous approach. Thus, this chapter aims to introduce an evaluation framework based on comprehensive criteria that assign buildings assembly impact scores simply to support the early stages of building envelope materials selection. The proposed framework is expected to estimate the environmental suitability of building assemblies (roofs and facades) in order to advance the cause of sustainable development.

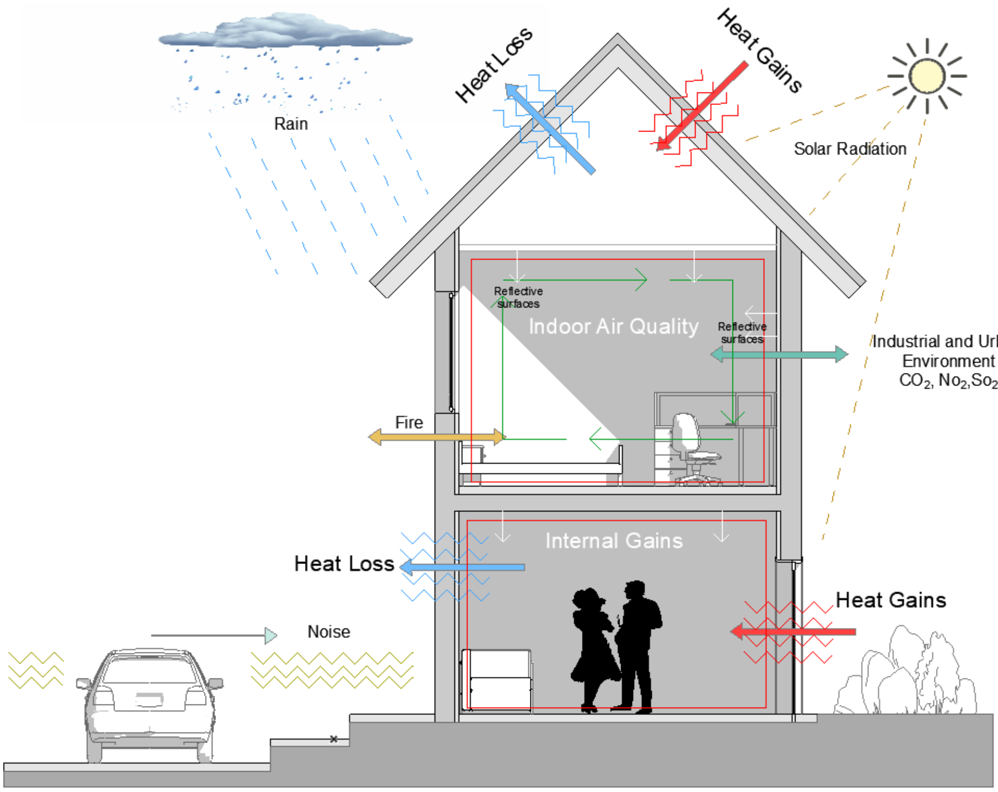


Figure 6-3: Environmental loads on building envelopes

6.2 Building envelopes assemblies and sustainability

The main role of the building envelope is to guarantee the indoor environmental quality and provide shelter and security against adverse environmental effects and consequently controls resources and energy consumption and environmental degradation (Natephra et al., 2018). As previously discussed, envelopes take on many roles; they play a significant role in determining the rate of raw materials use, controlling the indoor environment and minimizing the amount of energy required for heating and cooling (the most wasted energy in the buildings is through the walls, ceilings, and floors) (Luo et al., 2019). Also, they are vital in describing how a building is working effectively to provide visual and thermal control, natural lighting, indoor air quality control, noise reduction, moisture resistant, and fire resistance. Nonetheless, they have a significant impact on the initial and running costs of the building and further impact on local and global environments (Iwaro & Mwasha, 2013). This suggests the necessity of making building envelopes more environmentally responsible, economically affordable and ecologically sustainable than ever before. (See **Figure 6-4**)

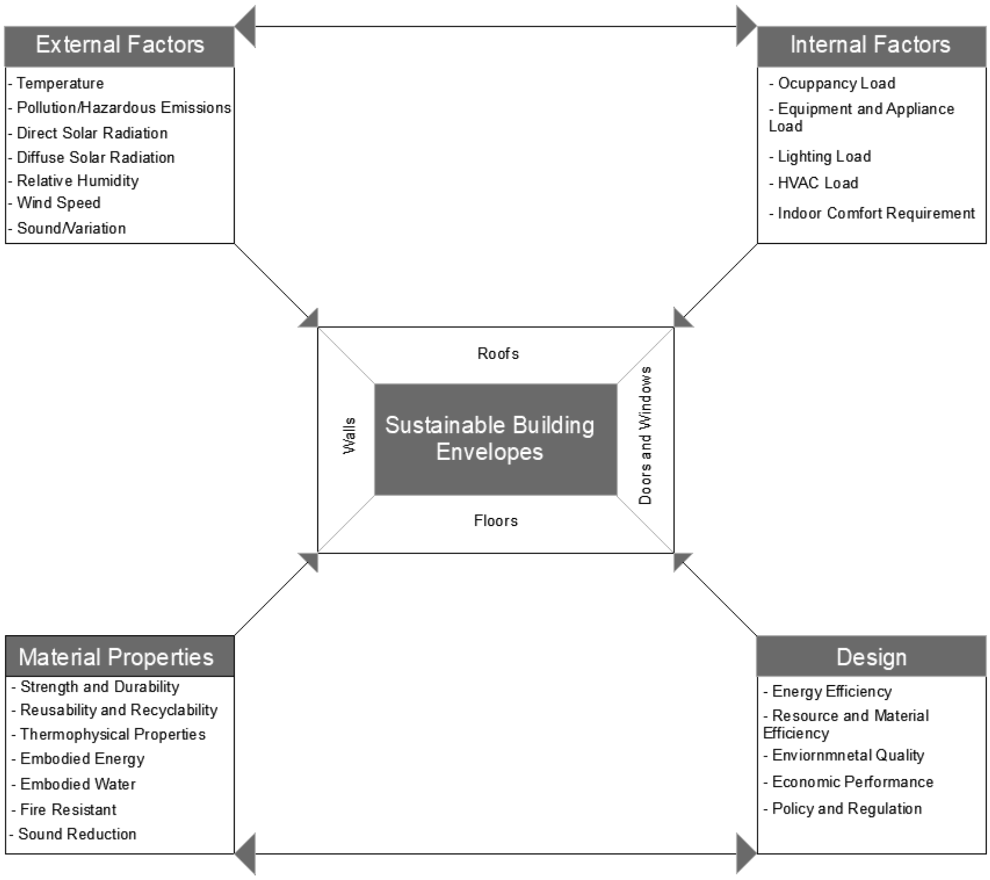


Figure 6-4: The link between building envelope and building sustainability

The environmental impact of building envelopes is an important sustainability factor that influences other factors such as energy efficiency and material efficiency. Nevertheless, the successful design of a sustainable envelope must apply all sustainable development factors when designing and selecting various envelope components.

6.2.1 Building Envelopes and Resource Efficiency:

Building envelopes are the largest-size building element and the most important parameter of the passive design strategies. A substantial amount of materials have been utilized to design different components of building envelopes which affect significantly resource consumption and environmental degradation (Manioğlu & Yilmaz, 2006). However, the most important strategies to optimize the resources use and reducing energy consumption in a building is the design for deconstruction or disassembly (Sanchez, Rausch, & Haas, 2019), and by applying the concept of reusability and recyclability when selecting various envelope components (I. Lee & Tiong, 2007).

According to Charls Kibert (1994), several Principles should be applied during the design stage to minimize the required materials include: 1) reuse materials if at all feasible; 2) use recycled or renewable materials; 3) ensure the materials used did not harm the environment in their extraction; 4) that toxics were not generated in the creation of the materials nor are they potential contributors to indoor environmental problems; 5) and that the design of the materials layout and detail is of high quality. See **Figure 6-5**

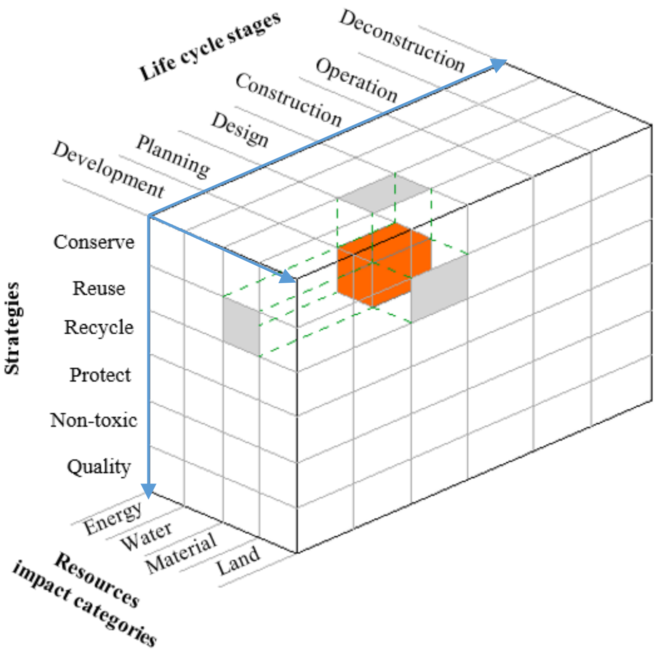


Figure 6-5: Design principles for materials and resources efficiency

Adapted from (Philip Crowther, 2005)

According to Stahel (2016), the recycling approach is the least effective approach to preserve scarce resources and should be implemented only when reusing building components is unfeasible. Additionally, the design for deconstruction (DfD) is a rising topic within manufacturing industries in which the building envelopes are carefully and methodically disassembled by closing material and energy loops (See **Figure 6-6**).

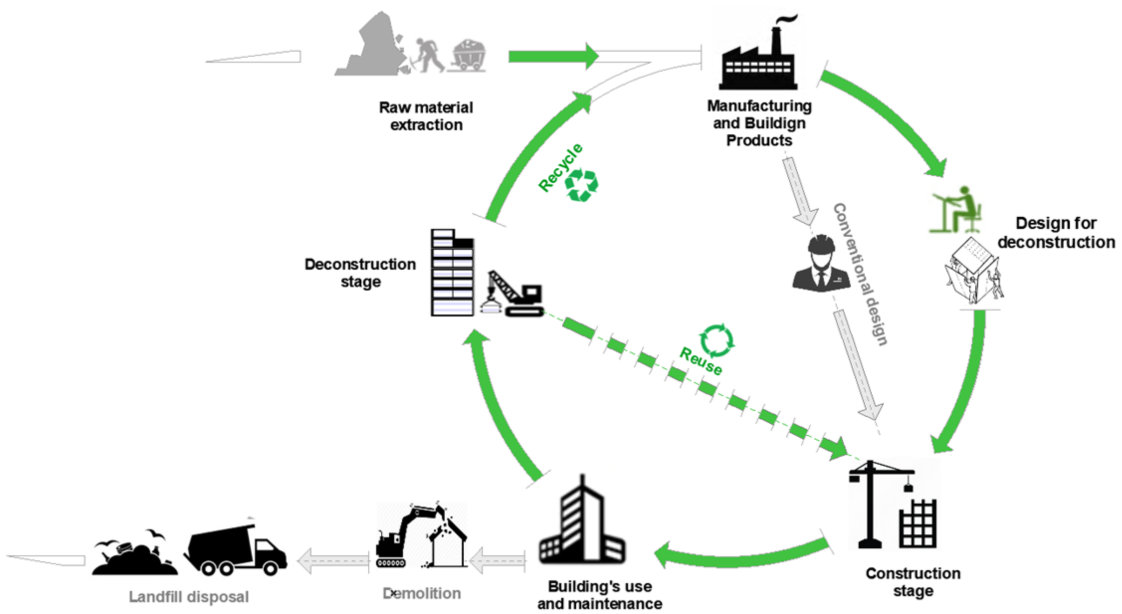


Figure 6-6: Design for disassembly in the building life cycle

According to Rios, Chong, and Grau (2015), deconstruction is the process of dismantling a building but restore the use of demolished materials. The disassembly of building envelope components have numerous benefits over conventional demolition or recycling approaches. The reuse of building components reduces the cost, resources and energy use, minimizes the carbon emissions and waste while extending the service life of building components (A. Akbarnezhad, Ong, & Chandra, 2014).

According to Guy and Giarimboli (2007), the key principles of design for deconstruction include: (1) appropriate documentation of materials and methods for deconstruction; (2) choosing materials based on their future impacts (Use recycled and recyclable materials); (3) create reachable joints between assemblies layers to ease the disassembling process and minimize or eliminate chemical connections while using mechanical and separating fixation; (4) Separate mechanical, electrical and plumbing systems from building assemblies to enable the disassembly of the components and materials for repair, replacement, reuse and recycling.; (5) design a human-scale and standardized materials and components to ease the dismantling process, facilitate reuse and allow for movement and safety of labours. However, selecting the proper material and components is perhaps the most significant design feature for the construction practitioners for achieving a high level of DfD (Rios, 2018). In the same line of thought, Philip Crowther (2003) identified 27 principles of DfD to be applied to the building if it is to be successfully disassembled. (See **Table 6-2**).

Principles of DfD as Applied to Buildings
1. Use recycled and recyclable materials.
2. Minimize the number of types of materials.
3. Avoid toxic and hazardous materials.
4. Avoid composite materials and make inseparable products from the same material.
5. Avoid secondary finishes to materials.
6. Provide standard and permanent identification of material types.
7. Minimize the number of different types of components.
8. Use mechanical rather than chemical connections.
9. Use an open building system with interchangeable parts.
10. Use modular design.
11. Use assembly technologies compatible with standard building practice.
12. Separate the structure from the cladding.
13. Provide access to all building components.
14. Design components sized to suit handling at all stages.
15. Provide for handling components during assembly and disassembly.
16. Provide adequate tolerance to allow for disassembly.
17. Minimize the number of fasteners and connectors.
18. Minimize the types of connectors.
19. Design joints and connectors to withstand repeated assembly and disassembly.
20. Allow for parallel disassembly.
21. Provide permanent identification for each component.
22. Use a standard structural grid.
23. Use prefabricated subassemblies.
24. Use lightweight materials and components.
25. Identify the point of disassembly permanently.
26. Provide spare parts and storage for them.
27. Retain information on the building and its assembly process.

Table 6-2: Comprehensive list of DfD principles as applied to buildings

Adapted from (Philip Crowther, 2003).

Although the design for deconstruction has shown several environmental, social, and economic benefits, many buildings have been designed without considering this concept

(Kanters, 2018). There are several barriers in designing the envelope components for deconstructibility (Rios, 2018). For instance, the fabrication of the various components requires the use of advanced techniques which might lead to extra cost, time, embodied energy and carbon emissions and the perceived risk in specifying reused building parts. Besides, there are no agreed guidelines yet on how to design buildings for deconstruction. However, evaluating and comparing the effects of deconstruction strategies on the overall life cycle of various building assemblies is crucial before making any decision (Coelho & De brito, 2013).

6.2.2 Building Envelopes and Energy Efficiency:

Many centuries ago, buildings have been constructed using highly reflective roofs and walls in hot climates and thick thatched roofs offered insulating properties in cold climates. Nowadays, the energy performance of building envelopes has been significantly neglected and many buildings are constructed that are leaky and have poor insulation properties. The energy efficiency of building envelopes are the most important factor that affects the energy consumed by heating and cooling loads. According to Sun et al., (2019), the walls are responsible for 25% of the energy consumption, followed by windows for 23%, roofs for 22%, and others for 30%.

The building envelopes have a major role to control the heat loss and heat gain between the indoor and outdoor environments and consequently affect the levels of the overall energy consumption and carbon emissions (J. Zhu, Chew, Lv, & Wu, 2013). A study prepared by the U.S Department of Energy (2012) shows that building envelopes are responsible for 73% of the total heat loss and heat gain.

Other studies recommend that 20–50% of the cooling and heating energy consumed in the building is due to the envelopes (Bano & Kamal, 2016; J. Yu et al., 2015). One possible way of how building envelopes can reduce the amount of heating and cooling loads is by controlling the thermal properties of the entire envelopes. The material's thermal conductivity, density, and specific heat capacity are the main factors affecting the building's envelope resistance and thermal mass.

Besides the thermo-physical properties, the reflectance of the building envelopes has a direct impact on the energy consumption and thermal comfort of the indoor spaces. One of the most important factors affecting heat transfer and energy consumption through the building envelope is the U-value (Ratnieks, Jakovics, & Gendelis, 2018). Over the years, code requirements of the thermal resistance (U-value) have upgraded substantially, and continue to increase in performance to reduce global energy consumption and greenhouse gas emissions (Sadineni et al., 2011a). For instance, the American Society of Heating Refrigerating and Air-conditioning Engineers (ASHRAE) has gradually upgraded the acceptable minimum thermal resistance standard of the building envelope (Wang et al., 2014).

Additionally, the colour of building envelopes affects the reflectance capacity of the external envelope surfaces and thus the solar heat gain and the overall cooling consumption of the buildings (Al-Obaidi, Ismail, & Abdul Rahman, 2014). However, it was found that a 30% reduction in solar absorption of the building envelopes can achieve a 12.6% savings in the annual required cooling energy (Cheng, Ng, & Givoni, 2005). According to Hu and Yu (2019), Thermo and light-responsive building envelope supports decrease the temperature of the façade surfaces and thus decreases the energy consumption and provides a better indoor thermal atmosphere.

In addition to that, building envelopes have the largest single contribution to the embodied energy of a building; associated with the extract, transport, install and disposal of the envelope components (Rios, 2018). Embodied energy might equal the operation energy over the lifespan of the building (Kanters, 2018). Therefore, Selecting low-embodied materials while incorporating durability, adaptability and deconstructibility when design building envelopes are considered the best strategies to minimize the embodied energy and to increase the envelope's service life. For instance, Densley Tingley (2012) estimated that approximately 49% of embodied energy saving can be achieved in a building when applying the design for deconstruction (DfD) approach.

Last of all, examining the thermal behaviour of the building envelope and its materials at an early design stage is considered the most important factor that could provide the highest thermal comfort in the interior spaces with the lowest use of mechanical equipment.

6.2.3 Building Envelopes and Economic Impacts

The impact of building envelopes on the overall initial costs is significant. According to Lee and Tiong (2007), building envelopes have the single largest cost in the construction of several buildings. The cost of building envelopes represents between 10% and 20% of the overall building cost (Jim, Jaggar, Peter, & Oluwole Alfred, 2016). Therefore, the management of the early cost of building envelopes can improve the cost certainty of building construction projects (Idowu & Lam, 2019).

Besides the initial cost; the maintenance and replacement costs have a major impact on the overall building life cycle cost. According to Flager (2003), the expenses associated with the repair and replacement of building components can cost over twice as much as the original capital cost (Over 50 years of life span). See **Figure 6-7**

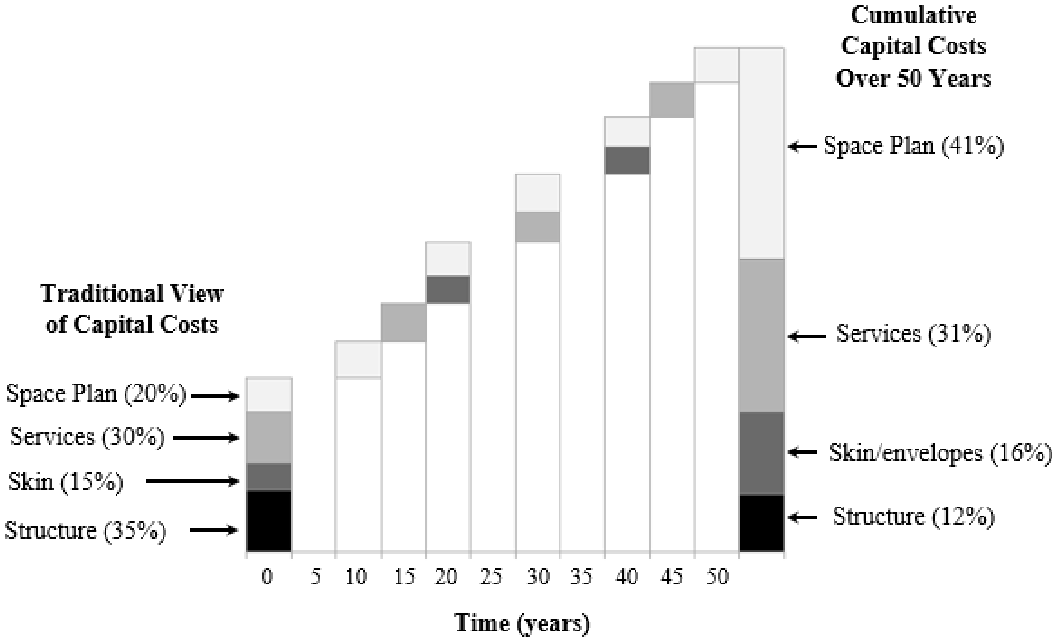


Figure 6-7: Life-Cycle Capital Costs

Adapted from (Flager, 2003)

The maintenance cost is vital for keeping the efficient operation and pleasing exterior of a building envelope. It includes all the activities to keep the building envelope in a good working condition, for example, cleaning of debris from roof drains, maintaining the sealants between envelope components, etc. In some cases, the maintenance of building envelopes can cost more than the initial material value, for example, the barriers and retarders between the internal and external finishing have a little percentage in the total envelope cost, but they become very expensive when maintenance is needed.

Additionally, the replacement cost (renewal costs) include costs to replace or refurbish the building envelope or its components when they get deteriorated or reached the end of their service time, for example, replacement of the roof tiles or façade claddings. Therefore, integrating durable materials into building envelope assemblies is expected to reduce the maintenance and replacement costs throughout the building lifetime. Nevertheless, life cycle cost (LCC) offers a comprehensive and reliable framework for distinguishing the exact economic paybacks of alternative building envelope assemblies.

Furthermore, the renovation work after the installation of building envelopes are usually difficult and cost much (Richard, Bataw, Waterman, & Greenhalgh, 2014). For example, fixing an acoustical problem for an existing building envelope is often a very difficult and costly job as it demands many technical and construction aspects (Ünver, Akdağ, Gedik, Öztürk, & Karabiber, 2004). **Figure 6-8** shows the relationship between cost and opportunity of change through the project life cycle.

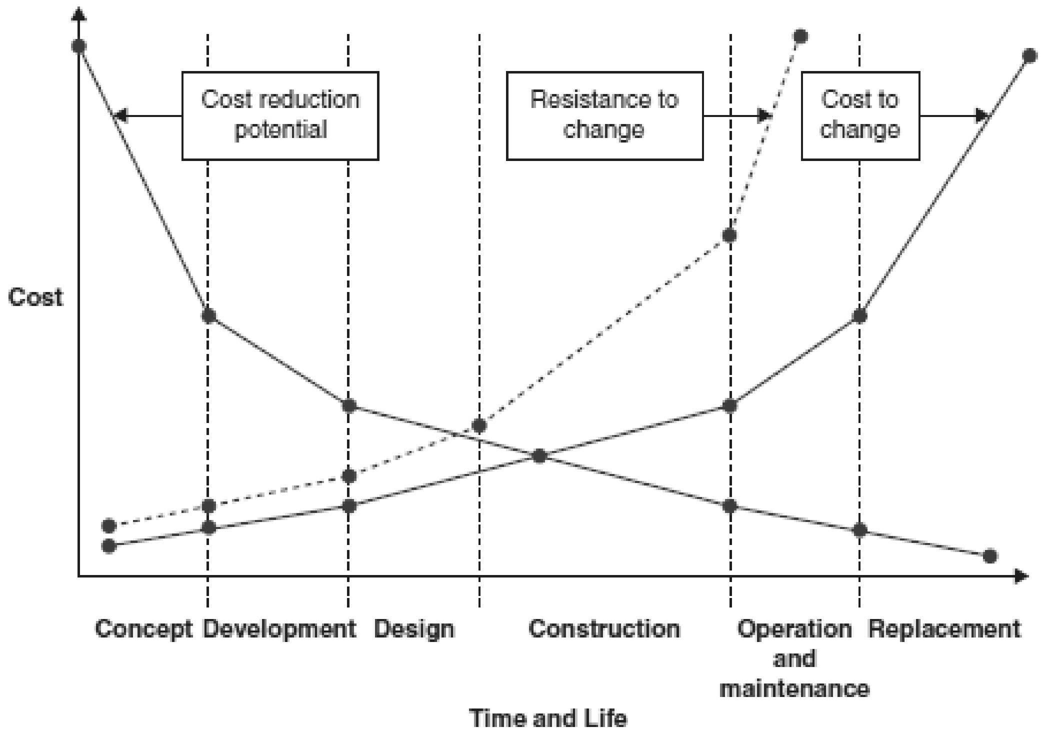


Figure 6-8: Relationship between cost and opportunity of change through the project lifecycle.
Adapted from (Richard et al., 2014)

6.2.4 Building Envelopes and Indoor Environmental Quality (IEQ)

The basic function of the building and its envelope is to provide a healthy and comfortable indoor environment for the occupants. As mentioned previously, a poor indoor environment increases the occurrence of many diseases and thus affects the health, productivity and comfort of the occupants (Sarbu & Sebarchievici, 2013). The indoor environmental quality (IEQ) is jointly linked to four aspects including thermal comfort, indoor air quality (IAQ), visual comfort, and acoustic comfort (M. H. Wu, Ng, & Skitmore, 2016; Zuhaib et al., 2018). Therefore, these factors can be used as assessment criteria to investigate the suitability of building envelope on the achievement of occupant's well-being. Frontczak and Wargocki (2011) stated that thermal comfort is the most widely used factor for the evaluation of indoor comfort compared with the other three factors. According to Oral, Yener, and Bayazit (2004), building envelopes should be designed as an element of a passive system with optimal performance to control heat, light and sound (See **Table 6-3**).

Properties of the opaque components of the building envelope	**Properties of the transparent components of the building envelope**
The thickness of the materials.	Dimensions of the transparent component.
The density of the materials.	The number of layers of the glazing.
Specific heat of the materials.	The heat transmission coefficient of the glazing.
Heat conduction coefficients of the materials.	Absorption, reflection and transmission coefficient of the glazing for solar radiation.
Light absorption and reflection coefficients of the surfaces.	The transmission coefficient of the glazing for diffuse sunlight.
Sound transmission coefficient.	The transmission coefficient of the glazing for direct sunlight.
Porosity and roughness of the surface.	The transmission coefficient of the glazing for sound.
The sound absorption coefficient of the surface.	Type of frame used for the transparent component.
Construction of the surface (fat, with interstices, ribbed).	Maintenance factor of the glazing.
Single or multilayer structure.	
Depth of the cavity between the layers.	
Thickness and sound absorption of the insulating material used inside the cavity	
Kind of connection between layers of different materials, and their number.	

Table 6-3: Physical environmental factors affecting the amount of heat, light, sound, and energy conservation in opaque and transparent building envelopes.

Adapted from (Oral et al., 2004)

6.2.4.1 Thermal Comfort

Thermal comfort can be defined as the condition of mind to determine the satisfaction level concerning the thermal environment, for example, too hot or too cold (ASHRAE Standard 55, 2004). Thermal discomfort such as overheated or too cold spaces can be connected to thermal stress and thus be responsible for poor health and bad performance of the building's users (Krü & Zannin, 2004). In general, the comfort zone can be determined when the majority of people reached the range of climatic conditions where they are satisfied with the heat or cold. The building envelopes are constructed to protect buildings and their users from harsh environmental conditions while providing thermal comfort. They protecting the indoor environment from direct solar radiation while reducing glare, providing natural lighting and ventilation, minimizing water penetration, and working as a thermal barrier (Mirrahimi et al., 2016). Thus, creating a thermally comfortable environment is considered one of the most important considerations when designing and selecting the envelopes of any building.

6.2.4.2 Visual Comfort

Visual comfort is connected directly with the presence of a good visual environment in terms of lighting conditions (Zuhaib et al., 2018). These conditions are characterized by many parameters such as illumination level, luminance distribution and brightness, the colour of light, luminous spectrum and glare, flicker rate and amount of daylight (European committee for standardization, 2011). According to Serghides, Chatzinikola, and Katafygiotou (2015), the presence of a good visual environment can add to the well-being and improvement of the comfort levels of the occupants. The light reflection coefficients of the envelope surfaces and their associated colours are of great importance (Oral et al., 2004). Commonly, components with light-coloured surfaces (high solar reflectance materials) reflect more light than those with dark-colour surfaces which improve the occupant comfort and the illumination of the indoor zones, while reducing building energy consumption (especially cooling energy summer months).

6.2.4.3 Acoustic Comfort

Acoustic comfort is another important aspect of indoor environmental quality. Acoustic comfort can be defined as the occurrence of a comfortable sound environment without any annoyance (Frontczak & Wargocki, 2011). The quality of a building to provide acoustic comfort significantly depends on the sound insulation performance of the building envelopes (Akdağ, 2004). According to ISO 16283-1 (2014), building envelopes play an important role in maintaining external and internal sound insulation. Additionally, increasing the mass of construction and combining different homogeneous and porous materials layers supports increasing the acoustic performance of the building envelopes (Miskinis, Dikavicius, Buska, & Banionis, 2018). The degree to which building envelope assemblies are effective in blocking sound is expressed as sound reduction index (R) or Sound transmission loss (STL). It is measured at sound frequencies from 125 to 4000 Hz and is expressed in decibels (dB) (Claudi et al., 2019). Nevertheless, properties such as density, stiffness and porosity are influencing the sound insulation of the construction materials (Januševičius et al., 2016).

6.2.4.4 Indoor Air Quality (IAQ)

Indoor Air Quality (IAQ) is known to have a diverse effect on human health as it is directly related to the ventilation and concentration of pollutants in closed environments (Zuhaib et al., 2018). According to ASHRAE Standard 62.1 (2007), the acceptable indoor air quality can be defined as "*air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction*". Various chemicals are emitted indoor from building materials and therefore occupants can be exposed to these chemicals by both the breathing of air and house dust. Furthermore, indoor air quality is also associated with indoor air relative humidity (RH) which consider an indication of moisture content presence. Moisture in building envelopes can cause severe defects to the indoor air quality which in turn cause various health hazards for the occupants and deterioration of the building components (Paul, Sree, & Aglan, 2010).

6.2.4.5 Building Envelopes and Fire Resistant Performance

Besides being the first line of defence against natural hazards, building envelopes play a major role to protect the building and its users from the danger of fire. The building envelope consists of multiple layers of materials (elements) with widely diverse properties relating to a fire (Jarnskjold, Jensen, & Knudsen, 2016). For resisting a fire all materials should have such properties that they can withstand fire for a longer duration. Fire protection requirements related to the exterior wall and roof envelopes are similarly critical performance aspects of these structures that must be cautiously measured when designing a building's enclosure system. Therefore, the designers have to make sure that the selected combination of materials delivers the required levels of fire safety in the building. Moreover, international building codes and other nationally recognized and adopted standards commonly assigned requirements on the fire resistance ratings (FRR) for the primary and secondary building components to protect the occupant's life and property. These fire ratings standards are mainly concerned with 1) maintaining the structural integrity of building components to prevent fire as well as smoke from breaching the compartmentation of the building, 2) controlling the insulation time of building components to withstand the heat generated from fire and prevent it from breaking the building compartmentation, and 3) ensuring the stability of building components to resist collapse as a result of heat from fire whilst maintaining their performance.

6.3 The optimization and selection of building envelope assemblies

The design stage of the building envelope is the most critical as the decisions made at this stage has a significant effect on the following stages of the building envelope's whole life (Žigart, Kovačič Lukman, Premrov, & Žegarac Leskovar, 2018). The building envelope combines a significant amount of construction materials and is a key factor of the embodied energy and other environmental impacts in buildings as well as it has an important impact on the operational energy in various types of buildings (Azari, Garshasbi, Amini, Rashed-Ali, & Mohammadi, 2016). The integration between several components of the building envelopes will influence the overall building performance.

As stated previously, it is more practical for the decision-makers to think in terms of building components and assemblies rather than individual building materials. For example, the evaluation of the overall fire resistance performance or sound reduction index of an assembled wall (composed of bricks, mortar, tiles, timber, plasterboard and insulation) is easier for designers than looking at the individual materials used.

In all, the determination of building envelope options having optimum conditions in terms of thermal and visual performance, indoor air quality, energy performance, acoustical performance, fire-resistant performance and technical data presentation on the envelope is a very important role in the design of a sustainable building. According to Žigart et al., (2018) for the maximum optimization of building envelopes, their materials and elements should be optimized individually.

Several studies investigated the optimization of building envelopes, for example, Azari et.al. (2016) presented a multi-optimization algorithm to investigate optimum building envelope design with regard to energy consumption and life cycle impacts in a low-rise office building in Seattle, Washington. They investigated various design inputs include insulation material, window type, window frame material, wall thermal resistance, and window-to-wall ratio (WWR). Huedo et al, (2016) created a model to investigate the sustainable selection of a different combination of building envelope assemblies and their environmental impacts in the early phases of materials selection. In their research, they selected several indicators that describe environmental emissions (global warming potential), use of resources (energy and water consumption), economic indicators (investment, maintenance, and energy costs), and indicators that describe complementary environmental information (non-hazardous and hazardous waste). Moussavi Nadoushani et al., (2017) developed a multi-criteria selection of façade systems by highlighting various economic, environmental and social criteria. The sustainable criteria include environmental impacts (embodied energy and carbon emissions, heating load, cooling load, resource sustainability), life cycle costs (material cost, labour cost, transport cost, maintenance cost, design cost), performance (weight, thermal resistance, thermal mass, acoustic insulation, resistance to decay), social benefits (aesthetics, suitability to location, suitability to climate).

Moreover, Kyriakidis et. al, (2019) examined the overall assessment of an environmentally responsive modular masonry wall system based on quantitative and qualitative criteria. The quantitative criteria include U-value, Time lag, decrement factor, embodied energy and carbon, while the qualitative criteria comprise structural performance, assembly and disassembly, ease of construction, construction time, reusability and recyclability, need for maintenance, and architectural expression. In the same line of thought, Iwaro and Mwasha (2013) examined the impact of sustainable building envelope design on the overall building sustainability by considering different parameters including external benefit, energy efficiency, environmental impact, material efficiency, regulation efficiency, and economic efficiency. In addition to the previous study, Iwaro, Mwasha, Williams, and Zico (2014) established an integrated criteria weighting framework for determining an integrated weight for criteria involve in assessing the sustainable performance and selecting a sustainable envelope design. Several criteria have been incorporated into their framework including energy efficiency, material efficiency, environmental impacts, external benefit, aesthetics, social benefit, envelope life span, recycling potential, affordability, maintenance and durability, and functional efficiency. Additionally, other sub-criteria have been identified along with the above criteria based on their relative importance index.

Furthermore, Zheng et al., (2010) developed a simple but reliable methodology for building envelope evaluation and optimization in the conceptual stage. A combination weighting system linking subjective weighting method and objective weighting method has been implemented to determine the weights of the main and sub-criteria. The main and sub-factors include thermal performance (heat transfer coefficient), building form (maximum form coefficient, perfect form coefficient, orientation, floor to ceiling height, window-to-wall ratio, shading coefficient of window glass), economy (initial and maintenance costs), innovation (new technology, new material and product), reliability (safety, comfort, and durability), and environmental protection. Also, Invidiata, Lavagna, and Ghisi (2018) developed multi-criteria decision making to improve the sustainability of the buildings by examined four design strategies involving thermal comfort, energy demand, Co_2 emissions, and cost.

Additionally, several studies have been conducted to examine the effects of envelope's types on the energy performance of specific buildings located in different climates (Ascione, De Masi, de Rossi, Ruggiero, & Vanoli, 2016; Eskin & Türkmen, 2008; Gossard, Lartigue, & Thellier, 2013; Gou, Nik, Scartezzini, Zhao, & Li, 2018; Jianying Hu & Yu, 2019; Lartigue, Lasternas, & Loftness, 2014; Méndez Echenagucia, Capozzoli, Cascone, & Sassone, 2015; Planas, Cuerva, & Alavedra, 2018; Sadineni, Madala, & Boehm, 2011b; Sang, Pan, & Kumaraswamy, 2014; Shoubi, Shoubi, Bagchi, & Barough, 2015), the façade colour (finish) and thermal mass on indoor temperature (Alonso et al., 2017; Cheng et al., 2005), the environmental impacts associated to the enclosure (Garcia-Ceballos, de Andres-Díaz, & Contreras-Lopez, 2018; Mostavi, Asadi, & Boussaa, 2017). Furthermore, other studies investigated the performance of phase change materials (PCM) in reducing the energy consumption and costs of building envelopes (K. O. Lee & Medina, 2016; Sharma & Rai, 2020; Thiele, Sant, & Pilon, 2015). Further information can be found in Appendix C-Table C1 regarding the multi-criteria optimization of building envelopes assemblies and materials.

According to the reviewed literature, there is still a challenge of defining the best criteria that can be used to assess the sustainable performance of the building envelope. One limitation in previous studies is the limited number of the examined criteria and indicators; which results in incomprehensible decisions concerning the optimization of the building envelope. In the other part, some common barriers have been noticed from the previous studies regarding the criteria used to evaluate the performance of building envelope assemblies, these might include:

• Each criterion has different relative importance according to the design objectives.

• Criteria might have different measurement units. To compare them, alternatives must be converted into a common base.

• Some criteria are quantitative (thermal conductivity, cost, etc.) and others are qualitative (external appearance, ease of construction, etc.).

• The synergies and trade-offs between criteria have not generally been taken into account. However, evaluating a single criterion does not deliver precise results because criteria tend to be inter-reliant. The above obstacles often make the decision-making process more complex, challenging, uncertain and vague and lead to subjective judgements in many cases. Therefore, a multi-criteria and multi-objective assessment methodology that can deal with these complexities have been proposed to produce a detailed decision support framework to help practitioners and decision-makers to select the best alternative building envelope assemblies from an early design stage.

6.3.1 Building envelope evaluation framework and indexes

The selection and evaluation of building envelopes are primarily handled by designers during the preliminary design phase. However, three interdependent processes are managed in this stage involve; identifying and selecting the most relevant systems among numerous alternatives, evaluating alternatives based on multiple criteria, and selecting the optimal option. See **Figure 6-9**

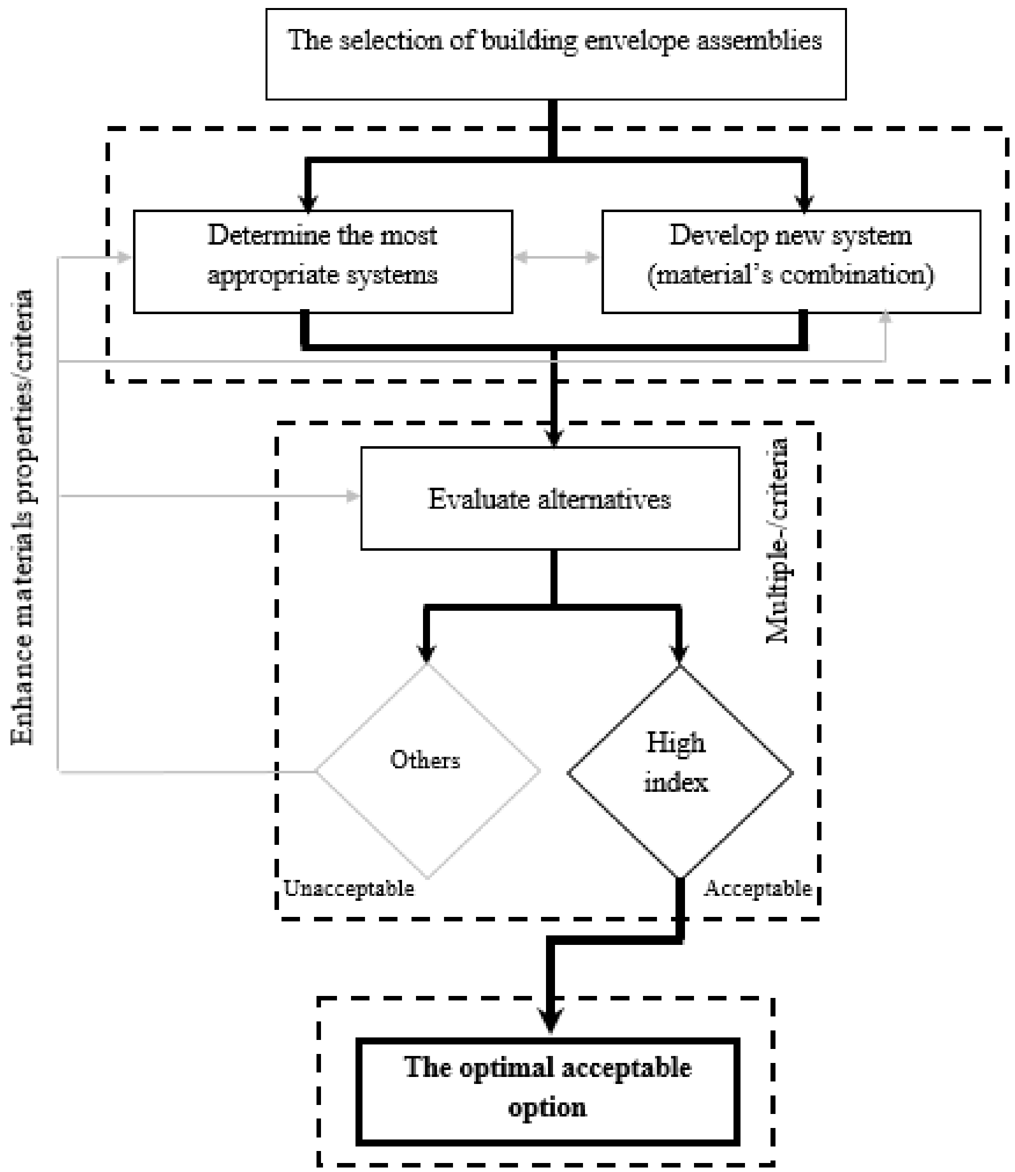


Figure 6-9: Proposed decision-making steps in building envelope selection process

The selection of building envelopes assemblies based on one pillar of sustainability (social, economic, and environmental impacts) may not provide a desirable solution. Thus, a systematic methodology based on a comprehensive list of sustainable criteria by accounting for the three pillars of sustainability is needed to identify the most sustainable alternative. The criteria have been identified to assist design teams in making applicable, knowledgeable evaluations and selections of building envelopes assemblies.

The essential criteria have been identified to assess the performance of envelope alternatives in order to achieve building sustainability. In addition to the criteria identified in the previous chapter, new criteria have been added in this chapter to cover all possible areas of optimization and to ensure that the environmental characteristics of the envelope can be regulated within acceptable limits. (See **Table 6-4**)

Main Criteria	**Sub-criteria**	**ID**
Material resource efficiency	Recycled content	MRE1
	Reusability and recyclability	MRE2
	Assembly and Disassembly	MRE3
	Durability	MRE4
Health and well-being	Human health impacts	HW1
	Moisture resistance	HW2
	Fire Resistant	HW3
	Embodied carbon	HW4
	Visual and thermal comfort	HW5
	Acoustic comfort	HW6
Socio-economic performance	Initial construction costs	SEP1
	Maintenance costs	SEP2
	Replacement costs	SEP3
	Demolition costs	SEP4
	Locally available material	SEP5
	Labour availability	SEP6
Energy efficiency	Embodied energy	EE1
	Thermal resistance	EE2
	Solar Heat Gain Coefficient	EE3
	Thermal transmittance of windows	EE4
Water efficiency	Embodied Water	WE1

Table 6-4: The main and sub-criteria for building envelope evaluation

6.3.1.1 Recycled content (MRE1)

Some building materials, such as metals, gypsum board and glass, can contain very high recycled content because of the integral nature of their production procedures and the availability of quality recycled materials in large enough quantities to satisfy their manufacturing requirements. Incorporating the recycled products into the building assemblies have the advantages of reducing the use of virgin materials, minimizing landfill, preserving material's embodied energy, cutting carbon emissions, and improving the environment. Nevertheless, it must be noted that achieving higher recycled content in an assembly doesn't always guarantee a lower impact. There are several other criteria to count when looking for green or sustainable materials.

On the other hand, several green building rating systems assigned some points to the material with recycled content. Most recycled content credits assigned by these systems are calculated by dividing the cost (value) of the recycled content in the material by the value of all the materials in the building. This indicates that when studying two materials that each have the same recycled content, the material with higher cost will contribute more for reaching the credit. However, this feature is considered one of the barriers facing designers and owners when dealing with sustainable certification as no one is in favour of paying more on materials to get more points. Yet, there is a need to create an efficient ranking scale to compare building envelope assemblies in terms of their percentage of recycled content.

If not provided by the manufacturers, the total recycled content of an assembly can be obtained by summing the proportional recycled content of each material in the assembly, and can be calculated by the following Equations:

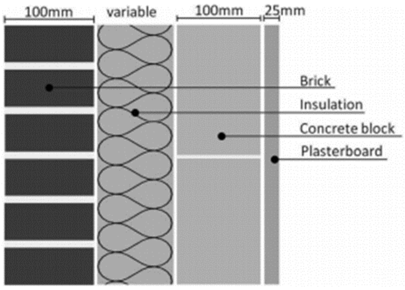
$RC_A = \Sigma\, PRC_M$ ………………………………………………………………. (25)

PRC_M = Weight of the material (per cent) × RC_M (per cent)……………..……..…… (26)

Weight of the material (per cent) = (Weight of material (lbs) ÷ Weight of assembly (lbs)) × 100 …………………………………………………………………………….... (27)

RC_M (percent) = Post-consumer content percentage + Pre-consumer content percentage…………………………………………………………………………(28)

Where RC_A is the assembly recycled content, RC_M is the recycled content of the material, PRC_M is the proportional recycled content of each material. **Table 6-5** demonstrates an example of how to calculate the recycled content of an assembly.



Building Assembly	Outermost layer				Innermost layer
Assembly layers (from the outermost layer)	Weight (%) to Total	Post-consumer recycled content (%)	Pre-consumer recycled content (%)	Proportional post-consumer recycled content (%)	Proportional pre-consumer recycled content (%)
Layer 1	46	30	50	13.8	23
Layer 2	1	0	0	0	0
Layer 3	48	0	0	0	0
Layer 4	5	0	0	0	0
Total weight	100				
Assembly post-consumer recycled content (%)				13.8	
Assembly pre-consumer recycled content (%)					23
Assembly total recycled content (%)					**36.8%**

Table 6-5: The recycled content estimation of a masonry wall assembly

Table 6-6 shows a point scale to rank alternative building assemblies in terms of recycled content percentage. The scale derived from published documents such as research papers, manufacturer's specifications, prevident systems, official government publications and reported statistics from the building industry.

Percentage recycled content of building assemblies (RC assembly mass)	**Points**	**status**
100%	10	High
≥75% and <100%	8	High
≥50% and >75%	6	High
≥25% and <50%	4	Medium
≥10% and <25%	2	Low
<10%	0	Low

Table 6-6: Percentage of recycled content of building assemblies

6.3.1.2 Design for disassembly /deconstruction (MRE2)

Design for disassembly (DfD) is a growing subject that aims to make the most of materials conservation from building end-of-life management and create adjustable buildings to prevent building disposal entirely. Bearing in mind that the expected functioning lifespan of modern buildings has become short as buildings are replaced for reasons of redevelopment and their incapability to remain functional within an alternative site use. However, these modern buildings, are not always materially or structurally deteriorated; the materials and components within them are so often useable (Philip Crowther, 2018). Therefore DfD can be an intelligent approach to encourage creative destruction and disposal of building components (Thomsen, Schultmann, & Kohler, 2011), and to close the construction materials' loop (Rios et al., 2015). The DfD has gained growing concern as a result of its increasing importance in the Circular Economy.

Buildings are typically covered with several envelopes which composed of a combination of pre-assembled components and on-site assembly of materials and components. One of the main obstacles in the recovery of building materials for reuse is the difficulty of separating various base materials and components from each other. For instance, the composites material, particularly incorporated into the roofing and building exteriors (ex. fibre-reinforced polymer), makes disassembly difficult and highly energy-intensive (Suffian, Dzombak, & Mehta, 2016). Nevertheless, the current construction practices still produce a fast assembly building (one-direction) without considering the significance of future disassembly (Salama, 2017).

According to Jouri Kanters (2018), less than 1% of existing buildings are entirely disassemblable. However, the recovery rate of waste materials from construction and demolition waste depends on the quality of the demolition and recycling process and the latter depends on the construction methods used to install the layers of different building envelopes. For this reason, the reusability and recyclability approaches can be optimized by selecting building assemblies in which mechanical fastening ("dry" construction) are applied more than adhesive or solvent-based installations ("wet" construction). The qualities of building assemblies connections are one of the main aspects that should be considered during the architectural design stage (Escaleira, Amoêda, & Cruz, 2019).

Building envelope components connected by simple mechanical and dry jointing connections (using screw, bolt, nut, etc.) may allow disassembly without the destruction of other parts and confirm reuse of the envelope's materials at the end of their lifetime.

According to Durmisevic (2006) and Escaleira, Amoêda, and Cruz (2019), the connections can be classified on a hierarchical order from rigid to flexible connections with regard to their effects on enabling reusing and recycling of building elements/components as follows:

I) Direct chemical connections (e.g. two components are permanently fixed, not allowing reuse nor recycling).

II) Direct integral connections between two prefabricated components (e.g. two parts are dependent on assembly/ disassembly, not allowing components reuse).

III) Indirect connections with third chemical material (e.g. two components are connected permanently with a third material, not allowing reuse nor recycling).

IV) Direct connections with additional fixing devices (e.g. two elements are connected with an accessory which can be replaced. If one element has to be removed then the whole connection needs to be taken apart).

V) Indirect/dry connections via dependent third component (e.g. two elements/ components are separated with third element/ component, but they have a dependence in assembly, restricting reuse).

VI) Indirect/dry connections via independent third component (e.g. there is dependence in assembly/ disassembly but all elements could be reused or recycled).

VII) Indirect/ accessory connections with an additional fixing device (e.g. with a change of one element another stays untouched (all elements could be reused or recycled).

Furthermore, using prefabricated[63] and modular building envelope components[64] take full advantage of the economic and environmental advantages of reusing and recycling materials. There are numerous reported advantages to modular construction including reduce on-site waste, enhance quality control, cut construction time, preserve embodied energy, reduce carbon emissions and pollution, enable easier reparation, and aid in the adaptability and deconstruction process. According to Densley Tingley (2012), approximately a 49% reduction in embodied carbon is achieved by applying DfD in the

[63] The process by which components of a building are manufactured off-site in a controlled location and then distributed to the project site and assembled.
[64] Generally, modular design separates a product into different components or sub-assemblies with standardized interfaces and reversible connections so that the components could be easily replaced and transformed.

building. Also, it has been stated that the refurbishing and reusing of modular buildings expend between 2 and 8.8% of the embodied energy needed for the manufacturing of new equivalent modular buildings (Ellen MacArthur Foundation, 2013). Hence, the ease and speed of deconstruction is a key factor that architects, engineers, and builders must consider when designing for deconstruction.

Table 6-7 shows the advantages and disadvantages of using different types of connectors.

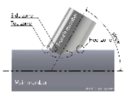
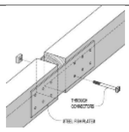
Type of connection	Example	Advantages	Disadvantages
Screw fixing		Easily removable	Limited reuse, both hole and screws, cost
Bolt and nut fixing		Can be reused many times	Can seize up, making removal difficult, cost
Nail fixing		Speed of construction, cost	Difficult to remove, removals usually destroyed a key area of the element
Welding		Adequate strength, cost	Difficult to remove, Hard to certify/inspect
Friction		Keeps the construction element whole during removal	Relatively undeveloped area, poor choice of fixing, structurally weaker
Mortar		Can be made to a variety of strength	Mostly cannot be reused, unless clay, the strength of mix often over-specified making it difficult to separate bonded layers
Resin bonding		Strong and efficient, dealt with awkward joints	Virtually impossible to separate bonded layers, the resin cannot be easily recycled or reused
Adhesives		Variety of strength available to suit the task	Adhesive cannot be easily recycled or reused, many are also impossible to separate
Riveted fixing		Speed of construction	Difficult to remove without destroying a key area of an element

Table 6-7: Evaluation of connection alternatives for deconstruction

Adapted from (Meg, 2008; Morgan & Stevenson, 2005)

One of the most significant factor to improve the deconstruction process is to facilitate the removal of layers which may contain systems of elements, components, and materials without subjecting other layers to damage where the dismantled layers could be reused, maintained or replaced (Elma Durmisevic, 2010). Independent parts within building envelopes should be assembled in an ordered configuration appropriate for accessing and disassembling. The Hierarchy might be composed of different levels, and each level represents a different intended service lifetime, in which, assembly parts with a longer service life should be placed in a higher level in the order and the fast-changing parts on a lower level (See **Figure 6-10**).

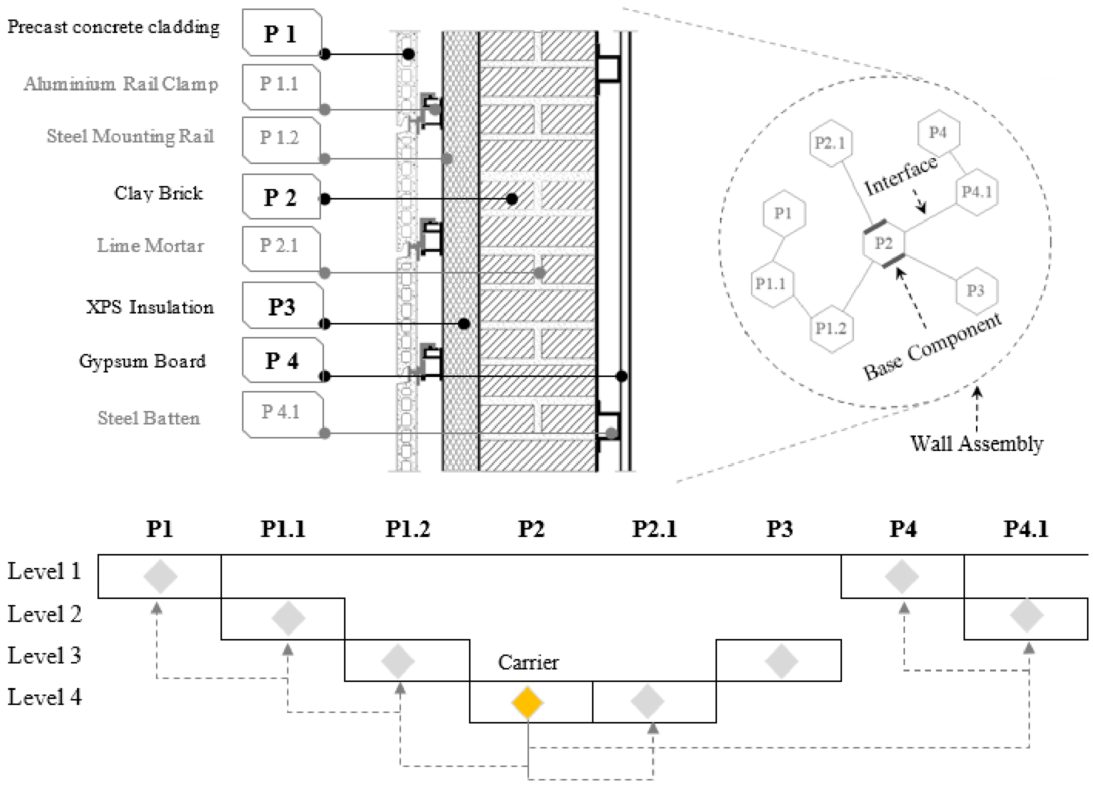


Figure 6-10: A hierarchical configuration of various parts within an external wall

Adapted from (Deniz & Dogan, 2014)

The above figure gives an example of an external wall façade assembly; precast concrete cladding has been used as an external finish, clay brick as a carrier and gypsum board as an internal finish. As shown in the figure, the external wall components are remained independent from each other by establishing dependent relation only to the carrier of the assembly (clay brick) to enable disassembly at the end of the building lifetime.

The following checklist can be easily applied to check if building assembly is easier to take apart (recovered) or not. See **Table 6-8**

DfD Checklist

1	**Hazardous materials are avoided (ensure safe reuse and recycling)?**	√
2	**Reusable or recyclable materials are used (materials worth recovering)?**	√
3	**Access to subassemblies has been considered; particularly those which need to be maintained, repaired, or modified regularly (decoupling of independent layers that have different degrees of durability?**	√
4	The start point for disassembly is identified?	√
5	Bolted and screwed connections are used rather than chemical connections?	√
6	The joints/connections between assemblies' layers are visible and accessible?	√
7	When possible, solid materials are used in place of composites of dissimilar materials?	√
8	Building assembly (infill materials) is separated from the structure[65]?	√
9	Building assembly is separated from mechanical, electrical and plumbing systems?	√
10	Human-scale and standardized materials are applied?	√

Table 6-8: Design for disassembly checklist

Note: Firstly, the three highlighted strategies (1, 2 and 3) are mandatory requirements for DfD. Secondly, if all the above-mentioned strategies have been noticed in a specific building envelope then the system might be fully disassembled at the end of the building lifetime, and if part of them exist, the system could be considered as partially disassembled. (More details in Appendix-G)

As noted in the previous chapter, the objectives of design for reuse and design for recycling are not identical, as design for reuse is mostly preferable to design for recycling. Reuse addresses that the envelope materials and components can be removed and separated from buildings while they continually maintain their qualities with negligible changes. On the other hand, the recycling approach is concerned with the utilization of materials produced from destructive disassembly processes that cause more damage to building materials and components. Many "wet" materials are not practicable for reuse such as cast-in-place concrete, asphalt paving, mortars, and paints, but maybe recycled or as a minimum not infect other recyclable materials that are linked to them.

If buildings envelopes selected to enable future disassembly[66] at the early design stage, then significant portions of materials could be reused and recycled and embodied energy

[65] In masonry building the load-bearing walls serve both as part of the structure and the building envelope. In modern buildings the function of the structure and envelopes are largely separated into independent building systems.

[66] While complete or full deconstruction is the preferred and most sustainable method for removing or renovating a building and its assemblies, it is not always possible due to the type of building and/or its components. However, a combination of deconstruction and demolition can be used.

recovery could be achieved. **Table 6-10** shows a ranking system to evaluate building envelope assemblies based on the DfD approach. The proposed assessment matrix can assist in the recovery and recycling of alternative building assemblies to reduce landfill volume and conserve resources.

End-of-life management of building assembly						
Fully disassemble	Partially disassemble	Demolish	Reuse/ Recover	Recycle	Landfill /waste	Points
×			×			10
×				×		8
	×		×			6
	×			×		4
		×		×		2
		×			×	0

Table 6-9: Disassembly assessment matrix to rank building envelope assemblies

6.3.1.3 Reusability and recyclability potential (MRE3)

Building envelopes are composed of several layers and each layer represents a different function and properties. The quality of the recovery at the end of the buildings lifetime is directly linked to the types of materials used in the construction of their assemblies. However, using reusable and recyclable materials in the construction of building envelopes and assemblies will facilitate the development of closed-loop material cycles and conserve resources, reduced the destruction of natural habitats and the resulting extinction of plant and animal species and reduced waste and pollution generation.

The recycling of materials, through reprocessing and remanufacture, is usually less efficient than the reusing process as there is little or no processing involved in the latter method. According to a previous study, up to 70% of the environmental impact could be reduced by applying reused materials in construction (Erlandsson & Levin, 2005). Despite the mentioned fact, the majority of materials used in today's buildings are down-cycled, not reused.

One of the greatest challenges relating to reusing materials is the low demand for such materials. However, as construction decision-makers start to implement the DfD strategy and identify the application of these materials, demand will certainly rise as a consequence. The potential of materials to be reused or recycled must be determined during the design stage of a building (Philip Crowther, 2005). **Figure 6-11** defines a point scale to estimate the suitability of individual building materials at the end of their lifetime.

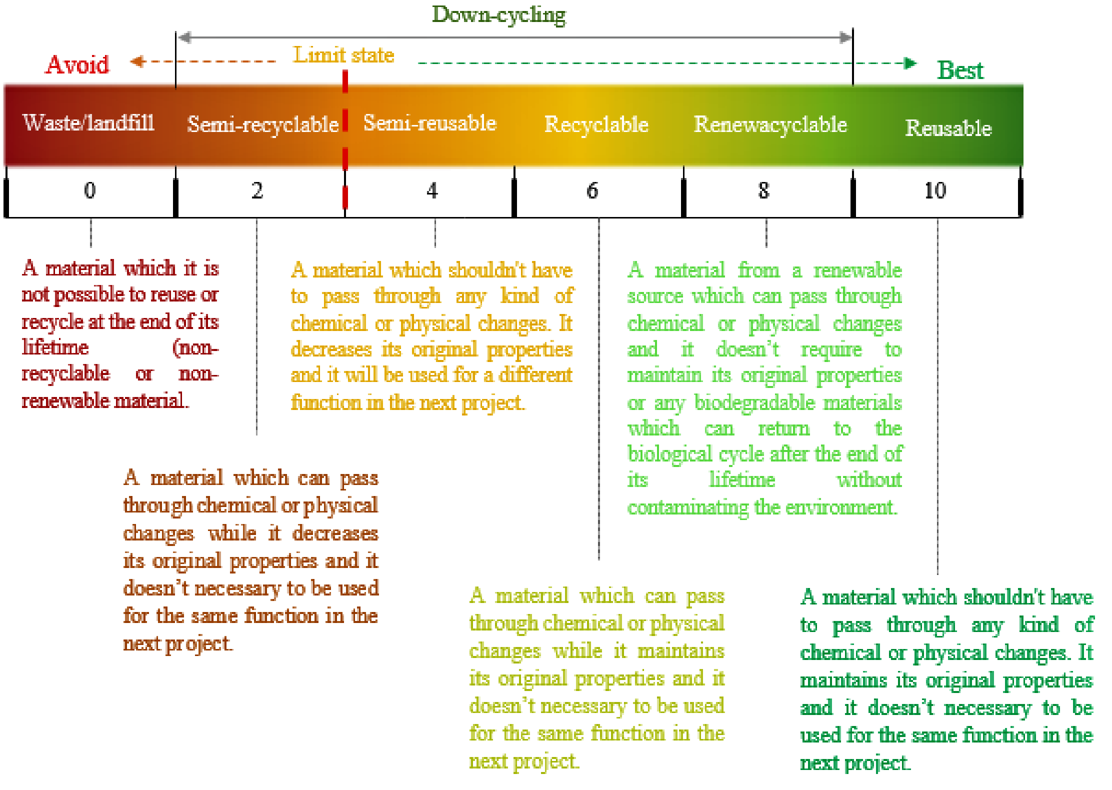


Figure 6-11: Categorizing and ranking building materials based on their use at the end of their lifetime

The graph is shaded in a gradation of colours transitioning from dark red to dark green. These colours represent the state of the materials at the end of their life include reusable, renewacyclable, recyclable, semi reusable, semi-recyclable, and non-recyclable or non-renewable. It should be noted that the definitions of the six categories can be changed from one project to another based on many factors such as site location and availability of recycling facilities.

While design for future reuse and recycle would have noticeable environmental gains for instance a feasible reduction in material waste, and a saving in energy consumption, there are also possible environmental burdens such as higher initial energy consumption and the potential use of more toxic materials attributable to their enhanced durability. Therefore, considering all these issues in a comprehensive framework is required to enable the selection of a sustainable alternative.

Furthermore, to rank building envelopes in terms of reusability and recyclability approach, each layer has to be examined individually and the average achieved points will be considered as an indication of their suitability for future recovery. See **Table 6-10**

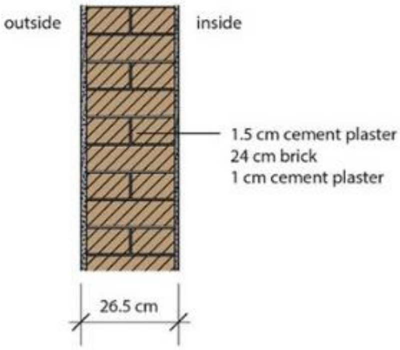
Alternative A	Outside		Inside	
Envelope layers	**Layer 1**	**Layer 2**	**Layer 3**	**Average achieved points**
Material name	C/S plaster	Fired-clay brick	C/S plaster	
Material's type	Semi-reusable	Semi-reusable	Semi-reusable	
Points	4	4	4	**4**

Table 6-10: An example of how to determine the total points of an alternative assembly in terms of reusability and recyclability approach

5.3.1.4 Durability (envelope life span) (MRE4)

Extending the useful life of an entire building envelope is the highest form of salvage and reuse. Generally, buildings are complex assemblies of multiple materials and components, which have widely varying lifespans. The life expectancy of building envelopes is commonly lower than the structural elements of a building that are protected from the external environment (See **Figure 6-12**). According to Crowther (2018), the building envelope is anticipated to last half or quarter as long as the building structure itself. This is mainly because building envelopes (skins) are more exposed to elements and various agents of decay which cause physical deterioration.

The design life of a building component can be specified in a range from 5 to 100 years typically when performing a life-cycle assessment for sustainability. According to Stewart Brand (1994), building skins are expected to have a minimum service life of 20 years and they should be adaptable to future reconfigurations. From a technical viewpoint, there is no durable or not durable material, there are only materials that under certain climatic conditions and interaction with other materials may last longer or a shorter time. In reality, the majority of building materials will need to periodically be replaced or repaired and maintained. If installed properly and coordinated with appropriate weather barriers and flashing materials, the building envelope can be considered to be "built to last." However, the optimal solution is to design building envelopes whose expected service life is equal to the service life of the building.

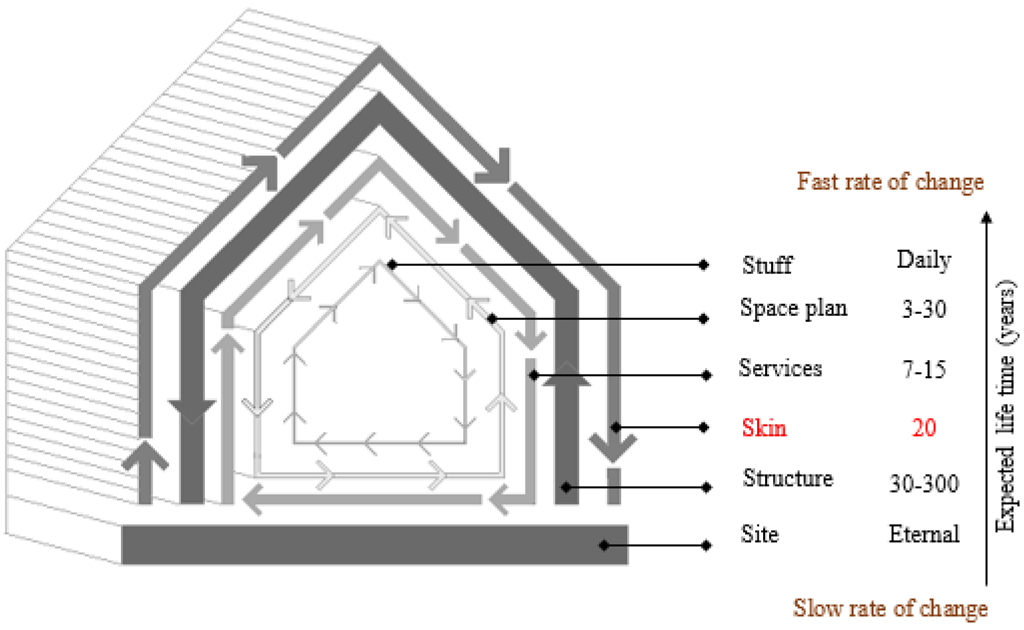


Figure 6-12: The six shearing layers[67] and their expected lifetime

Adapted according to Stewart Brand (1994)

Typically, the design for long-life components and products is based on three strategies to repair and upgrade; standardization, modularity and functional separation (Cooper, Skelton, Moynihan, & Allwood, 2014). As indicated beforehand, different building layers within an assembly have distinctly different life expectancies. Each layer alters at a different level and affects the adjacent layers. Therefore, building assembly should be designed in a way that the layer of a shorter design life can easily be replaced and installed over a layer of longer design life (functional segregation). In other meaning, no material with a longer lifespan must be dismantled for maintenance or replacement of another material which most susceptible to failure (Elma Durmisevic, 2010).

The entire durability of envelope elements should be tackled through material selection; however, the relative or differential durability between inter-reliant components requires delicate thought during the selection process. A simplified method for assessing the service life of buildings and components has been described in **Table 6-11**.

[67] **Site**: the geographical setting, the urban location and the legally defined lot; **Structure**: is the main supporting frame of the building; **Skin**: is the envelope of the building, the barrier between inside and outside that allows for control of the internal atmospheric conditions and resists the external weather; the outside walls, facade and roof; **Services**: are the mechanical and electrical systems of the building; **Space plan**: is the internal partitioning and fixed furniture of the building; **Stuff**: the furniture and other goods in a building that can change frequently.

The life expectancy of building envelopes	Points	Category
≥ 100	10	Permanent life
≥75 and <100	8	Long life
≥50 and <75	6	Medium-long life
≥25 and <50	4	Medium life
≥20 and <25	2	Short life
<20	0	Temporary life

Table 6-11: The life expectancy of building materials and the assigned points

The above method, however, should be combined with the analysis of the potential durability of reused materials, as they can become "weak elements" within the building`s structure and in consequence, lower the operational durability of a building. The challenge is not to make building envelopes more durable rather than reusable or recyclable, but to use durable materials that are worth recovering for reuse and/or recycling. The ultimate durability and circularity of building envelopes is not only related to the durability of its materials but more importantly to the way that the materials are put together

In conclusion, selecting building materials and assemblies to support durability, disassembly and reuse from an early design process can reduce waste (high-value recovery) and extend building useful life, providing economic and environmental benefits during the whole life cycle of the building and its systems and materials.

6.3.1.5 Human health impacts (HW1)

The improvements in sampling methods in addition to the analytical techniques have substantially produced a new level of detailed research on emissions from construction materials and products (Willem & Singer, 2010). In recent decades, building materials are often made of chemicals produced in a factory and sometimes combined with organic compounds, making the selection of materials and their parts more complicated than ever before. Many construction materials like adhesives, finishes, sealers, and coatings contain harmful chemical substances that can release in use or during removal, leading to an adverse effect on the construction workers and end-users exposed to them. These chemicals appeared in many forms including gases, vapours, fumes, dust, and mists.

Therefore, the first question that must be asked before selecting any material is: what are the impacts of this material on human health and the environment?

Designers and architects are responsible for the evaluation of the environmental and human health impacts of building materials and assemblies from an early design stage. They should attempt to avoid or minimize those substances in material selection by answering three questions; 1) where does a product come from?; 2) What is it made of? ; 3) Where does it go at the end of its life?. The information related to the hazardous materials can be acquired from a various sources, such as manufacturers and distributors, government resources and standards, tools developed by organizations, materials safety data sheets, and government agencies fact sheets (Meg, 2008). Nevertheless, choosing products that have been tested against the common hazardous components[68] is a simple way to reduce the concentrations of these contaminants while improving human health and well-being.

Furthermore, to minimize the number of chemical substances within building envelopes, the following strategies and actions might be used during the selection process:

- Address product material requirements with suppliers.

- Select assembly which designed from simple materials of simple origin and ingredients.

- Select assembly which composed of a few numbers of layers.

- Minimize the selection of on-site wet construction materials.

- Select assembly in which mechanical fixation is used rather than chemical fixation.

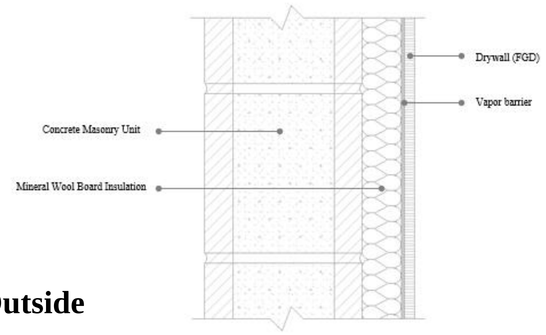
On the other hand, selecting a low-emitting building envelope is a complex task as it requires a detailed investigation of the health impacts of the individual materials and their ingredients within each assembly and then reporting the concentration level of any known chemical substances. However, if any layer contains hazardous substances, then it is necessary to look for a more benign alternative, where appropriate in the context of the project.

In general, concentrations of chemicals contained within a given assembly or material can be expressed as part per million (ppm) or as percentages, with 100 ppm = 0.01%, 1,000 ppm = 0.1%, and 10,000 ppm = 1.0%. However, the lowest achieved score (points)

[68] Lead, asbestos, and polychlorinated biphenyl (PCB) are often found in ageing construction materials, such as paint, sealant, roofing mastics and membranes, and plaster.

among the assembly layers will be assigned as an overall score for the building assembly in order to ensure that a healthy alternative is selected free from carcinogenic chemicals. **Table 6-12** shows an example of tracking and evaluating the layers of a typical drylined hollow block construction in terms of hazardous substances.

Alternative A
Typical drylined hollow block construction assembly



Outside → **Inside**

Envelope layers	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**
layer's name	Concrete masonry unit	Steel studs	Mineral wool board insulation	Vapour barrier	Drywall (gypsum board)
Known hazardous	-	●	●	-	●
Hazardous chemicals names	-	Aluminum Powder (pyrophoric)	Urea phenol formaldehyde	-	LEAD, MERCURY, ARSENIC, CADMIUM
Concentration rate %	-	0.01	2.06	-	<0.01 each
Recommendation	-	Moderate concern	Avoid		High concern
Points score	0				

Table 6-12: An example of how to determine the final score of an alternative assembly in terms of hazardous content

It can be seen from the above example that the overall achieved points for this assembly is 0 as it contains carcinogenic substances in three layers (Urea phenol-formaldehyde in layer no 3 (high concentration level), pyrophoric in layer no 2, and LEAD, ARSENIC, MERCURY AND CADMIUM in the layer no 5).

The above approach can be used to optimize the building envelopes by eliminating chemicals known that pose a hazard to human and environmental health, while enable redesigning or reformulating the building assembly and its layers. (More details can be seen in Appendix-H).

5.3.1.6 Moisture resistance (HW2)

Building envelopes must be constructed according to design specifications to integrate moisture and mould prevention measures. Building materials that get wet during construction or constructed wet may grow mould, corrode or deteriorate which negatively lead to structural failures and health problems (Kreiger & Srubar, 2019). It is generally accepted that the majority of all building envelope problems are caused by excess moisture. Such problems begin when assemblies accumulate moisture faster than their ability to store or dry (moisture storage capacity is exceeded). Assemblies with a large amount of moisture storage capacity will be able to store moisture. In fact, recent building envelopes assemblies have less moisture storage capacity than those of the past so that it is more sensitive to leaks.

Moisture problems in the building envelope are usually caused by the passage of water or water vapour from the inside or outside of the building into the building envelopes and accumulating inside them. According to Tenwolde and Rose (1996), the migration of moisture occurs by four mechanisms; 1) liquid flow by gravity or air-pressure differences; 2) capillary suction of liquid water in porous building materials; 3) water vapour by air movement; 4) water vapour diffusion[69] (J. F. Straube, 2002). Still, vapour diffusion represented the smallest amount of the above moisture transfer mechanisms and so is less likely to cause severe damage to a building. (See **Figure 6-13**)

Managing rainwater penetration into walls, roofs, and windows should be a designer's main concern since water leaks are typically the major and most obvious moisture cause. Furthermore, proper selection of building envelopes can help reduce risk and make a building more tolerant of moisture. Architects and designers have to ensure that materials within building envelopes meant to remain dry when enclosed from outdoor weather or within unventilated assemblies. Therefore, the following steps must be followed to control moisture in building envelopes:

1. Test the moisture content of materials especially those that can easily store a great deal of liquid water before closing them in cavities or applying adhesives or finishes to them.

[69] Vapor diffusion is the movement of water vapor molecules through porous materials (e.g., wood, insulation, drywall, etc.) as a result of differences in vapor pressure. Vapor pressure differences occur as the result of variations in air temperature and sources of humidity, such as occupants, showers, pools, plants, etc.

Moisture content analysis is a critical component that significantly impacts the physical properties and materials quality at all stages. Water is added to some materials during installation (e.g., concrete, water-based coatings, wet-spray fireproofing and wet-spray insulation). However, these materials must be allowed to dry naturally, or force-dried using specialized equipment before being enclosed in building assemblies, for instance, concrete masonry units or porous insulation must be dry before they are enclosed by gypsum board walls Also, porous materials such as wood, medium-density fiberboard (MDF) are susceptible to mould growth if their moisture content is too high. According to Wu and Piao (1999), the commercially available oriented standard board (OSB)[70] showed a 31% dimensional increase when it is moisture content reached 24%. Also, the American Wood Council (2018) stated that high moisture levels in wood members can result in up to 70% loss in their mechanical properties.

2. Inspect and verify the outermost surface material and flashing details for the roof, walls, windows, doors and other penetrations to prevent liquid water from entering the envelope.

The traditional envelope assemblies rely on the outermost face material to be sealed to resist weather-related water as it is considered the first defence against rainwater. Additionally, flashings are an important line of defence in a building's moisture protection assemblies. They used to stop and direct the flow of water to designed drainage pathways. The successful performance of a face seal scheme demands that all joints between the exterior face cladding and other components and connections be part of the face seal. The following typical flashing details must be checked:

I. Flashing within walls above doors, windows and other wall penetrations.
II. At the top of the exposed walls.
III. Flashing where a lower story roof, balcony or deck intersects upper story walls.
IV. Flashing at roof edges, gutters, and roof drains.

3. Verify that building envelopes have rainwater protection in the form of air gaps and barrier materials to keep water from wicking further into the envelopes.

Water and air barriers are critical for controlling the most important moisture sources in buildings and should be used in most climates. Air barriers are designed to prevent the

[70] Oriented strand board (OSB) is similar to particle board, normally used in the construction of load-bearing applications, it designed by compressing wooden strands in particular alignments and bonding by adding adhesives.

flow of air, and the moisture attached to it, from entering a building envelope. Air leakage by convection transfer accounts for over 200 times the amount of moisture transmitted by vapour diffusion (Diane & Richard, 2002). Moreover, the location of the air barrier within the envelope assembly is commonly not considered crucial, and it is not controlled by the particulars of climate. Nevertheless, designing a building envelope to be sufficiently airtight is a very important strategy to limit water vapour migration by airflow, also, to minimize or restrict heat loss and gains through conduction, convection, and radiation.

In general, designers must ensure that a continuous air barrier from the roof-wall intersection to the above grade wall-foundation intersection is provided. A single membrane could perform as an air and water barrier if proper materials are chosen. An air barrier membrane is often water-resistant and needs to be impermeable to air, structurally rigid, continuous and durable. If a single material used as a vapour and air barrier then its location must be considered carefully[71]. In general vapour barrier should be located on the exterior (outside of the insulation) in warm climates, and in cold climates, it will be on the interior (inside of the insulation). In mixed climate (both heating and cooling are required), a vapour barrier is placed on either the interior or exterior side of the insulation or omitted altogether (A. A. Mark et al., 2001).

Besides the air barrier, a drained cavity system[72] will provide fair to good protection in almost all climates and building exposures, and should be considered as a broadly applicable wall design approach for moisture protection. The drained cavity system is also called a rain-screen system[73] which is designed to allow the remaining components of the wall assembly to effectively manage the moisture passed through the external envelope layer to provide a long-lasting, energy-efficient, and high-performance wall assembly. On the other hand, waterproofing is required to keep the roof water-tight since they are exposed to the weather, especially for flat roof construction. Flat roofs[74] are being more commonly used in new constructions instead of pitched roofs (M. Gonçalves, Silvestre, de Brito, & Gomes, 2019). In contrast to the flat roof, the water run-off layer on a pitched roof must be rainproof but need not be waterproof (Andrea & G. H., 2005).

[71] The vapor barrier should always be located on or near the warm side of walls, floors, and ceilings.

[72] A drained cavity works as a secondary barrier to water penetration and provide a means to drain water that may have pass through the first envelope layer.

[73] The system demands better planning, construction detailing skills, and on-site quality control.

[74] A flat roof is specified by a slope lower than 5° and should not be used in regions with possibility of rain or snow without the application of a proper waterproofing system.

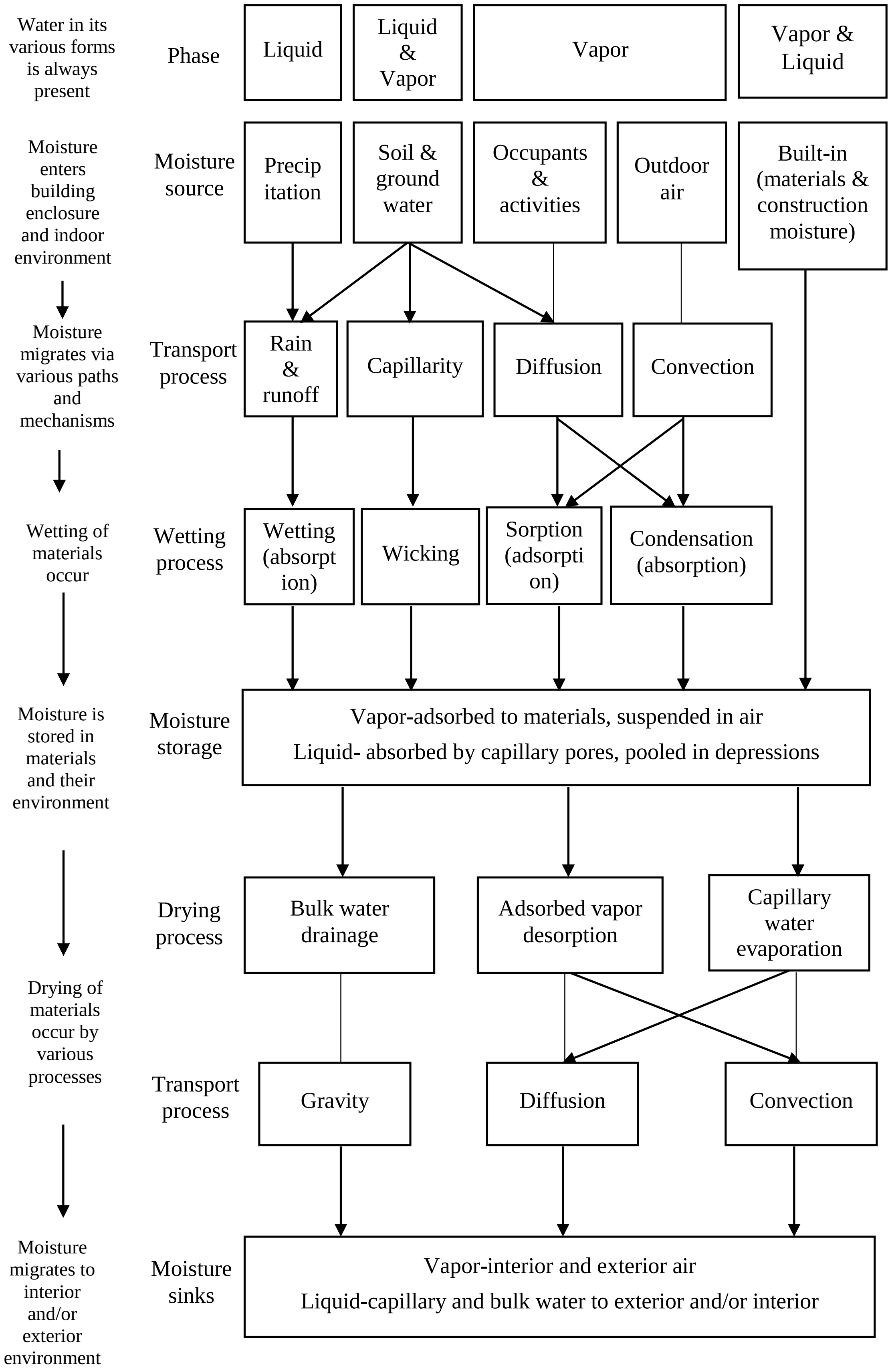


Figure 6-13: Moisture sources, processes, storage and sinks.

Adapted from (Kesik, 2016a; J. F. Straube, 2002)

In brief, the selection of building envelopes that exhibit a high tolerance for the moisture should be done very early in the concept stage before construction initiates in order to ensure that moisture control policies are effectively implemented. In this regard, the building envelopes should be selected based on three principles; checking the moisture content of the materials (use moisture-tolerant materials), the ability of the assembly to control liquid water, and manage condensation.

Table 6-13 shows a ranking scale for selecting moisture-resistant building envelopes (walls and roofs). The proposed method outlines some major issues but is not intended to be comprehensive and the ratings may be subject to adjustment by experience.

Wall assemblies				
Moisture content	Face seal and flashing details (first defence barrier)	Drained cavities (secondary defence barrier)	Air/vapour barrier (second defence barrier)	points
Good	Good	Good	Good	10
Good	Good	Poor	Good	8
Good	Good	Good	Poor	6
Good	Good	Poor	Poor	4
Good	Poor	Good	Good	2
Other options				0
Roof assemblies				
Moisture content	Roofing cover and flashing details (first defence barrier)	Waterproofing layer (second defence barrier)	Air/vapour barrier (Third defence barrier)	points
Good	Good	Good	Good	10
Good	Good	Good	Poor	8
Good	Good	Poor	Good	6
Good	Good	Poor	Poor	4
Good	Poor	Good	Good	2
Other options				0

Table 6-13: Moisture performance rating scale to select the most informed building assemblies

Note:

• Good – the system is likely to meet or exceed acceptable performance expectations.

• Poor – the system may require careful attention to detailing or has a relatively high risk of not meeting acceptable performance expectations.

Table 6-14 gives examples of how various assemblies can be ranked based on their moisture performance.

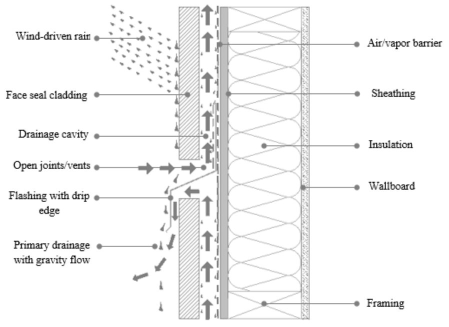
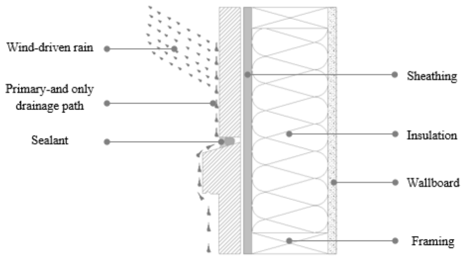
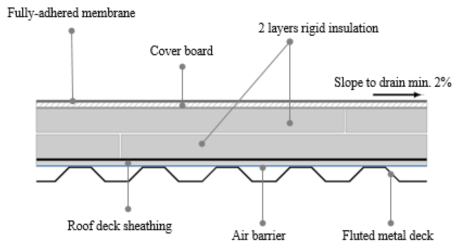
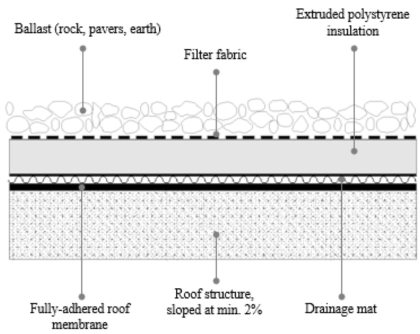
Wall assemblies alternatives		Moisture content	Face seal and flashing details	Drained cavities	Air/ vapour barrier	Score
A		Good	Good	Good	Good	10
B		Good	Good	Poor	Poor	4
Roof assemblies alternatives		Moisture content	Roofing cover and flashing details	Waterproofing layer	Air/ vapour barrier	Score
C		Good	Good	Good	Good	10
D		Good	Good	Good	Poor	8

Table 6-14: An example of ranking alternative building envelopes (walls and roofs) based on their moisture-resistant performance

6.3.1.7 Fire Resistant (HW3)

Fire-resistance ratings can apply to and protect structural and non-structural elements of a building such as beams, columns, walls, floors and roof construction. Building assembly's fire-resistance rating (FRR) identified the period the assembly will serve as a barrier to the spread of fire and how long the assembly can function structurally after it is exposed to a fire. Fire-resistance rating is specified in building codes primarily as a matter of life safety and secondary as property protection. Building codes in various countries use fire-resistant rating in different ways for a different part of the building based on building's type, height and occupancy, for example, low rise building structures and assemblies (4 stories and below) may be designed to have lower FRR than high-rise buildings because in the latter people need a long time to escape.

Furthermore, the modern architectural envelopes and the use of new materials have given new challenges to fire safety design. The fire performance of building envelope assemblies should be optimized during the building design process. Fire resistance ratings are most often specified in hours or minutes, with typical values ranging from half an hour to 4 hours (Buchanan & Abu, 2017). **Figure 6-14** gives a ranking scale to state the fire performance of building assemblies (walls and roof assemblies) as hours of fire resistance.

		Structural elements/ walls for low rise building (4 stories or less)		Structural elements/ walls for medium and high rise building (more than 4 stories)		
FRR (minutes) load-bearing walls and parts with high risk of fire spreading	<60	≥60 and <90	≥90 and <120	≥120 and <150	≥150 and <180	≥180
Points	**0**	**2**	**4**	**6**	**8**	**10**
FRR (minutes) Non-load bearing walls and Roofs	<20	≥20 and <30	≥30 and <40	≥40 and <50	≥50 and <60	≥60

Figure 6-14: Fire resistant rating scale for building envelope assemblies

Materials and construction assemblies that provide fire resistance, measured in terms of fire endurance time, are commonly referred to as fire resistance-rated-construction or fire-resistive materials and construction. Building materials like gypsum board, concrete, pre-manufactured concrete and clay block products are commonly used to protect a building element from fire. However, a fundamental understanding of the characteristics of materials within building envelope assemblies is crucial to describe their fire performance. The fire-resistance rating of multi-layer assemblies is based on the fire resistance of each layer. It must be noted that the proposed ranking scale applies to the outer walls and roofs. More examples are shown in **Table 6-15**.

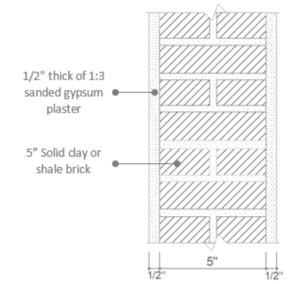
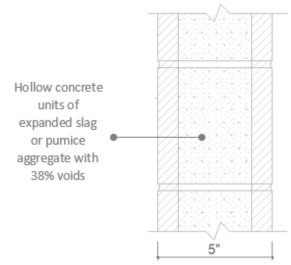
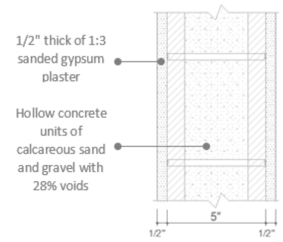
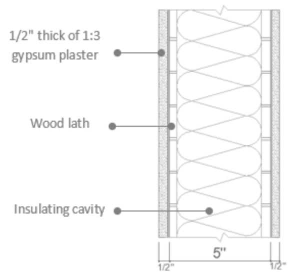
Building envelope assemblies	thickness	Structural Type	Fire-resistant rating (FRR)	Construction Details	points
Solid clay or shale brick; 1/2" thick 1:3 sanded gypsum plaster facings on both sides.	5”	load-bearing	2hrs 30 mins		8
Hollow concrete units of expanded slag or pumice aggregate with 38% voids, no facing.	4"	Non-load bearing	20 min		2
Hollow concrete units of calcareous sand and gravel with 28% voids, 1/2" of 1:3 sanded gypsum plaster facings on both sides.	5”	load-bearing	2hrs 30 mins		8
2" x 4" stud wall; 1/2" thick 1:3 gypsum plaster on wood lath on both faces; insulated cavities.	4 1/2"	Non-load bearing	1hr		10

Table 6-15: Fire resistant rating and ranking of various wall assemblies

Adapted from (National Institute of Building Sciences, 2000)

6.3.1.8 Embodied carbon (HW4)

Buildings contribute significantly to carbon emissions worldwide. Embodied carbon contributes around 11% of all global carbon emissions and the direct and indirect carbon emissions from buildings are expected to twofold in 2050 (IPCC, 2014; Pomponi & Moncaster, 2016). Previous studies showed that carbon emissions emitted from material consumption should unquestionably be the focal point of carbon control (Cabeza et al., 2020; Teng & Pan, 2019). Therefore, selecting low carbon materials and assemblies from an early design stage to reduce carbon emissions is a matter of importance for sustainable development (Monahan & Powell, 2011). The importance of addressing embodied carbon emissions on account of construction will increase as low-carbon energy capacity improves and building operational energy efficiency upgrades. Reducing embodied carbon is important for reducing resources and associated costs while improving building sustainability. **Figure 6-15** shows high opportunities to reduce the carbon footprint from the early planning and design phases.

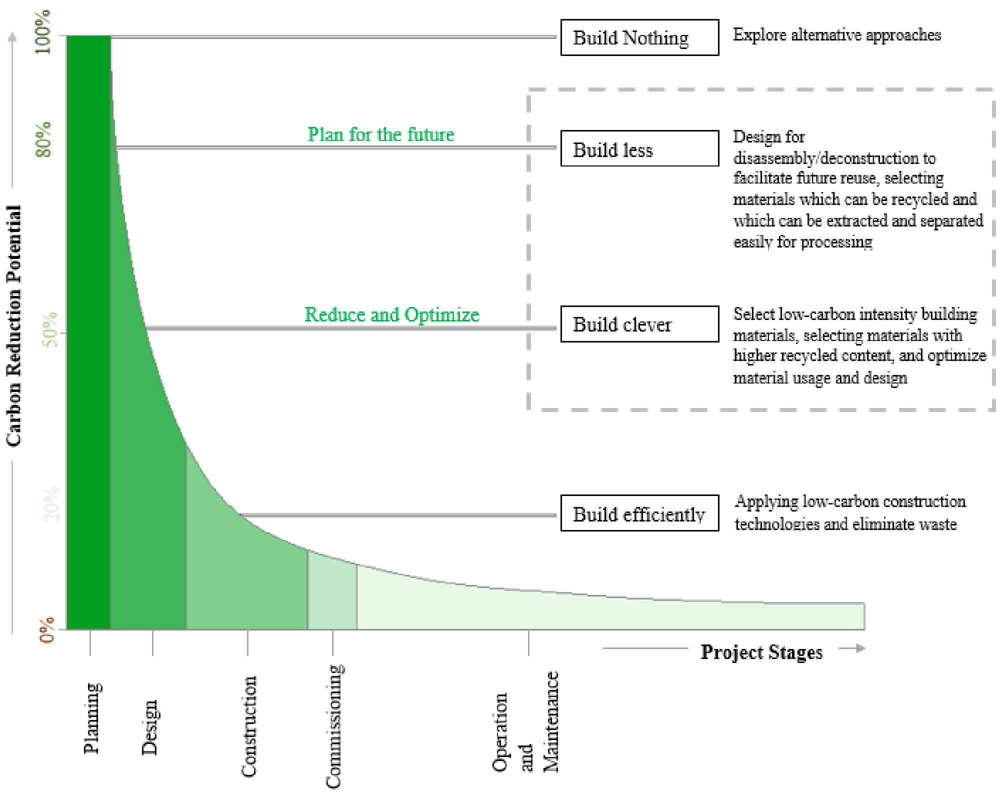


Figure 6-15: Carbon reduction potential throughout the project stages

Adapted from: (HM Treasury, 2013)

In general, building structures such as foundations, slabs and columns often represent the biggest contribution to embodied carbon because of the large volumes of material they use. Also, the building envelope is known to be associated with the greatest impact on carbon emissions (Hammad, Akbarnezhad, & Oldfield, 2018). For instance, a building façade constructed with a large amount of aluminium cladding and glass (ex. Aluminum Curtainwall systems) can contribute significantly to the total carbon emissions of the building as both materials have carbon-intensive production processes (Volf et al., 2018). However, Identifying which layer of the building envelopes and assemblies hold the most significant proportion of the overall embodied carbon can lead to significant reductions. Along the same line, decision-makers should find the perfect balance between selecting materials with a low embodied carbon and achieving an appropriate U-value for the building envelope to ensure reducting the whole operational energy.

On the other hand, many strategies and measures have been suggested in research and practice to reduce the embodied carbon of building materials and assemblies while achieving flexible and adaptable design, for example:

I) Choosing longer-lived building materials and assemblies, and layering the building envelope components in an order based on their repairing and replacement cycles.

II) Increasing use and integrate local materials into building envelope assemblies.

III) Replacing carbonate-containing materials[75] with non-carbonate materials (bio-based alternatives) such as substitute concrete or steel with a wooden, natural rock instead of ceramic.

IV) Using supplementary cementitious materials, for example, fly ash, slag blended cement and limestone cement and ground-granulated blast furnace slag.

V) Making optimal design and reducing the number of materials[76], for example, reducing the thickness of structural members and building envelopes while meeting the structural requirement.

VI) Using pre-fabricated structures and assemblies instead of cast-in-situ. These measures should better inform building design decision making.

Furthermore, embodied carbon is linked to other criteria such as embodied energy, recycled content, reusability and recyclability, design for deconstruction, and others. More details have been illustrated in **Table 6-16**.

[75] Also, applying simple measures, such as using wood frames instead of aluminium frames for windows, could make a great change in reducing the carbon footprint of the building assemblies.

[76] Omitting the layer that is purposing to support an aesthetic function in the design of building façade and cladding can reduce the number of employed materials and consequently the embodied carbon footprint of the facade.

Carbon saving action	Strategies and measures	References
Using fewer materials	Make optimal building form (e.g. compact building's height; width; and depth).	(Azari et al., 2016; Lotteau, Loubet, & Sonnemann, 2017)
	Modify the measurement for building elements while maintaining structural requirements (e.g. changing the thickness of the structural and envelopes elements).	(Hawkins, Orr, Ibell, & Shepherd, 2020)
	Design for off-site construction (e.g. fabrication and assembly of building elements in purpose-built off-site factories).	(Teng & Pan, 2019)
	Design for reuse and deconstruction (e.g. increasing the reuse of materials from demolition; design a building for deconstruction at the end of its life; design a building for easy reconfiguration during its life.	(Densley Tingley & Davison, 2012)
Using alternative materials	Select lower carbon intensities materials (e.g. sustainably-sourced timber).	(González & García Navarro, 2006; Piccardo, Dodoo, & Gustavsson, 2020)
	Select higher recycled content materials (e.g. higher recycled content blocks, and locally recycled aggregates).	(Xiao, Wang, Ding, & Akbarnezhad, 2018)
	Select locally-sourced materials with lower transport-related carbon emissions.	(Leo Samuel et al., 2017)
	Select durable materials (e.g. facades and fixing components that last as long as the building frame).	(Chastas, Theodosiou, Kontoleon, & Bikas, 2018)

Table 6-16: The types of actions and measures a design team should consider for embodied carbon reduction

Adapted from (WRAP, 2013)

The assessment of embodied carbon of construction envelopes and assemblies requires two key pieces of data: the mass of each constituent material and the embodied carbon intensity by kg of each material. In the early design phase, the available information is often not sufficient for making a detailed assessment of embodied impacts. Therefore, the selection of low-embodied carbon assemblies can be addressed indirectly by checking other criteria. **Table 6-17** demonstrates in simple steps for design professionals and consultants to rank alternative building envelope assemblies by checking areas that influence the embodied impacts.

Low-carbon intensity materials / supplementary cementitious materials are used instead of carbonate-containing materials (≤ 0.05 kgCO2/kg)[77]	Locally-sourced materials are integrated	Higher recycled content assembly ($\geq$50%)	Assembly can be fully or partially disassembled /Assembly components can be reused or recycled	Durable assembly ($\geq$25 years)	Prefabricated assembly	Points
●	●	●	●	●	●	10
At least 4 of the above criteria are included						8
3 of the above criteria are included						6
2 of the above criteria are included						4
1 of the above criteria are included						2
None of the above						0

Table 6-17: Ranking scale for the selection of low-embodied carbon assemblies

It should be noted that the strategies discussed above are intersected and can sometimes be considered both positive and negative. Besides, the emission reduction potential of each design strategy is heavily influenced by several factors such as climate, topography, building code requirements.

6.3.1.9 Visual and thermal comfort (HW5)

A well designed visual environment, with the appropriate use of colour and lighting, will have important benefits for human health and wellbeing. In this regard, the interior and exterior finishes of building envelope assemblies play a significant role in the enhancement of the quantity and quality of visual and thermal comfort of the building. The solar reflectance of the innermost layer of the building envelope has a major impact on the quality of the indoor light. Also, the emissivity and the solar reflectance of the outermost envelope layer play a significant role in energy-saving for buildings especially in tropical climates (Košir et al., 2018).

The solar reflectance value, or reflectivity, is the measure of visible and usable light that reflects a surface when illuminated by a light source. The surface reflectance of the innermost layer of the building envelope plays a major role in the optimization and reflection of natural lighting and electric lighting in indoor spaces. Therefore, solar reflectance values of the walls, ceiling, and floors within the space should be kept as high as possible. When higher reflectance surfaces are applied, more light, from all sources, is reflected in the space, and luminance levels are increased.

[77] Flyash= 0.008 kgCO2/kg; Straw= 0.01 kgCO2/kg; Rammed soil= 0.023 kgCO2/kg.

Furthermore, the building envelope external surface temperature is substantially influenced by the received solar radiant heat flux and surface solar absorptivity. Building envelope finishes with high solar reflectance and thermal emittance can decrease temperature and the solar radiation heat absorbed by the building envelopes (including roofs and exterior walls), and consequently reducing the building cooling energy needs and power demand (Paolini et al., 2017; Shi & Zhang, 2011). Moreover, the optical parameters of the building exterior surface are also considered are important factors in controlling the overall urban solar albedo of the built environment.

Table 6-18 shows how various building assemblies can be ranked based on their solar reflectance (SR) and solar reflectance index (SRI) values.

SRI / External surfaces	<20	≥20 and ≤35	>35 and ≤50	>50 and ≤65	>65 and <80	≥80
Points	**0**	**2**	**4**	**6**	**8**	**10**
SR / Internal surfaces	<20	≥20 and ≤35	>35 and ≤50	>50 and ≤65	>65 and <80	≥80

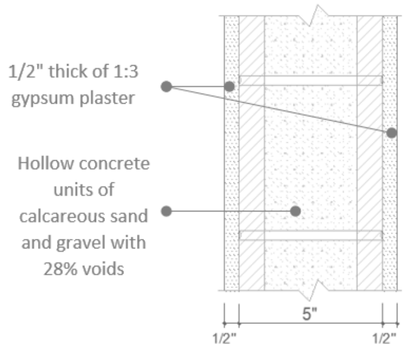
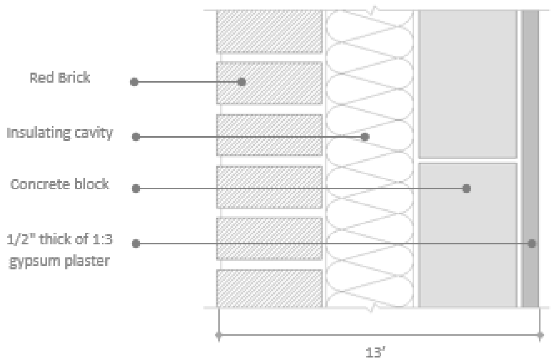
<table>
<tr><th></th><th>Building envelope assemblies</th><th>SR</th><th>Points</th><th>SRI</th><th>points</th><th>Final points</th></tr>
<tr><td>A</td><td>
</td><td>73</td><td>8</td><td>90</td><td>10</td><td>8</td></tr>
<tr><td>B</td><td>
</td><td>73</td><td>8</td><td>40</td><td>4</td><td>6</td></tr>
</table>

Table 6-18: The rank value and the average points of SR and SRI for alternative building envelope assemblies

Also, the window to wall ratio (WWR) has a significant impact on the daylighting and thermal load performance of buildings (Chi, Wang, Wang, Li, & Peng, 2020; L. Wen, Hiyama, & Koganei, 2017). The WWR represents the percentage of façade area installed with glazing; the higher the WWR, the greater the floor space is available for visual contact and daylighting. Nevertheless, a high WWR may lead to a heating or cooling penalty (Harmati & Magyar, 2015; Marino, Nucara, & Pietrafesa, 2017). Therefore, an optimization approach might be used to find moderate values between opaque and transparent surfaces of the building envelopes.

On the other hand, the proper selection of windows also enhances thermal comfort and brings about a prominent energy saving in artificial lighting (Acosta, Campano, & Molina, 2016). In this line of thought, visible transmittance is the most important factor used to control daylight admittance and to reduce electric lighting, while sustaining the occupants' well-being and satisfaction.

The Visible Transmittance (VT) is an optical property that specifies the amount of visible light transmitted through the windows (a higher value allows more light to be transmitted and is desirable to maximize daylight) (Cuce & Riffat, 2015). However, the glazing type[78], number of panes, the frame of the window, sashes, grids, and glass coatings affect the VT value. For instance, the VT value decreases when a low-emittance (low-E) coating is added and reduces substantially when a tint is added. The Low-emittance coatings are mainly metals or metallic oxides that aim at allowing a great amount of the visible light to be transmitted while preventing much of the other wavelengths which affect undesired solar heat gain. The tint glazing is produced by attaching small metal oxides with different colours (grey, green, blue, and bronze) to the float or rolled glass components. The tinted glass is used to reduce solar transmittance and undesired glare (Cuce & Riffat, 2015).

Also, adding another layer of glass also lessens VT[79]. The VT varies between 0 and 1, the higher the VT value, the more light is transmitted through windows (maximizing daylight). The VT can ranges above 0.90 in the case of uncoated clear glass and less than 0.40 for highly reflective coatings on tinted glass. Some examples of visible transmittance for various types of glazing are given in **Table 6-19**.

[78] Various glazing technologies are used worldwide including vacuum glazing, smart glazing, PCM glazing, self-cleaning glazing, and etc. however, each glazing technology has some particular advantages and disadvantages depending on its performance in many aspects.

[79] The number of panes and the inert gas type remarkably affect the visible transmittance and the thermal performance of the multi-pane glazing.

Glazing Type	Visible Transmittance (VT)
Single Glazed	0.90
Double glazed (Air filled)	0.81
Conventional double glazed unit	0.81
Double glazed unit with Low-E coating	0.74
Argon-filled double glazed unit with Low-E coating	0.74
Polycarbonate panel	0.72
Double glazed (Argon filled)	0.70
Triple glazed (Krypton filled)	0.62

Table 6-19: Visible transmittance of various glazing types

Adapted from (GÜNDOĞDU & KUNDURACI, 2019)

Moreover, there is a requirement to balance the needs of higher VT value to increase the building's daylighting versus the need to minimize solar gains through windows especially in hot-climates (Alhagla, Mansour, & Elbassuoni, 2019). Normally a reduction in solar heat gain coefficient (SHGC) comes in a reduction of visible transmittance (VT)[80]. However, with the advancement of high-performance glazing systems, it is possible to select windows that can minimize the excessive solar heat gain while letting the visible light pass through it. See **Figure 6-16**

VT	<0.50	≥0.50 and <0.60	≥0.60 and <0.70	≥0.70 and <0.80	≥0.80 and <0.90	≥0.90
Points	0	2	4	6	8	10

Figure 6-16: The ranking scale of windows based on their VT value

6.3.1.10 Acoustic comfort (HW6)

Although acoustic quality is a key factor for occupants' productivity and well-being, it has been broadly neglected during the material selection stage and this often leads to rework after the occupation of the building in order to solve noise problems. According to previous studies around 80 million people are subjected to undesirable noise level and approximately 170 million people live in areas where noise causes adverse health effects and serious annoyance (Claudi et al., 2019). Therefore, it is essential to take measures to protect indoor spaces and their occupants from noise.

[80] The relationship between SHGC and VT is sometimes given by the light-to-solar-gain ratio (LSG), calculated by LSG = VT/SHGC. An LSG greater than 1 means a window has managed to keep its VT high while lowering its SHGC.

The building envelope has the main opportunity to protect the indoor environment from unwanted noise by specifying high sound-quality walls, roofs, windows and doors. The sound insulation of a building depends upon its performance in reducing the airborne and impact sound transferred by all sound paths, direct and indirect. The reduction in airborne noise of a roof or wall construction is referred to as the sound reduction index (R) also called sound transmission loss (STL) and it is a single number expressed in decibels (dB) (Luisa F.Cabeza et al., 2019). This index specifies the number of decibels by which the sound is weakened as it passes through the component. The higher the sound reduction, the better the sound insulating property is. Generally, single skin constructions show the lowest reduction index and the sound insulation of lightweight assemblies is less than that of heavyweight components. (See **Table 6-20**)

Material or Type of Construction	Average Sound Reduction (dB)
Plastered masonry wall made from calcium silicate bricks (240 mm, density class 2.0).	58
Plastered masonry wall made from lightweight vertically perforated clay bricks, 115 mm.	47
Lightweight plasterboard wall with one layer of plasterboard, 75 mm.	44
Lightweight plasterboard wall with two layers of plasterboard, 150 mm.	53
Multi-ply timber element, 135 mm.	37

Table 6-20: Sound reduction indexes of some building assemblies
Adapted from (Eckard & Müller-BBM, 2009)

The following Equation is used to estimate the sound reduction index (ISO 10140, 2010):

$$R = L1 - L2 + 10\log\left(\frac{S}{A}\right) dB \qquad (29)$$

Where: $L1$: the average sound pressure level in the source room in dB; $L2$: the average sound pressure level in the receiving room in dB; S: the total surface of the tested module in m^2; A: the equivalent sound absorption area in the receiving room given by Equation:

$$A = 0.163V\,T \qquad (30)$$

Where: V: the volume of the receiving room in m^3; T: the reverberation time of the receiving room in s.

Furthermore, the quality of the fenestration and wall connections can have a remarkable effect on the total sound reduction index of a building envelope. Commonly, when a poor sound insulation component is used in a building facade (ex. window or door), the combined sound reduction index for the assembly is mostly closer to that of the poor component. The combined sound reduction index of a building façade with various elements can be estimated by using the following formula (ISO 10140, 2010):

$$R = -10log\left(\frac{1}{S}\left(S_1 10^{-R1/10} + S_2 10^{-R2/10} + \dots\right)\right) \dots\dots(31)$$

Where: R1 and R2 are the individual reduction indexes of the materials; S_1 and S_2 are the individual area of each façade element S: the total façade area.

Globally, building codes instruct a maximum allowable interior noise exposure from external sources for all new buildings. Nevertheless, considering acoustic control in the design phase of a project will allow for more cost-effective design, as well as more control over the outcome. The average ambient background noise in metropolitan, urbanized areas typically varies from 60 to 80 dB, for example, a busy road could produce a sound level of 80 dB (Berglund, Lindvall, Schwela, & World Health Organization, 1999). However, the aim of assigning a minimum sound transmission loss of the building assemblies is to bring the sound within a space back to what we would call normal ambient sound, which is around 30-40 dB. **Figure 6-17** gives a point scale to rank building envelope assemblies based on a common basis for the prediction of sound insulation properties.

	Very poor	Poor	Fair	Good	Very good	Excellent
Sound Transmission loss (dB)	<30	≥30 and <35	≥35 and <40	≥40 and <45	≥45 and <50	≥50
Points	0	2	4	6	8	10

Figure 6-17: The ranking scale of building assemblies based on their Sound Transmission loss value

6.3.1.11 Initial construction costs (SEP1)

Building envelopes have a significant impact on the initial and running costs of the building. The building's developers are always looking at building envelopes that have minimum initial and running costs to maximize their investment returns. The initial costs are one of the main concerns for the building stakeholders when evaluating the building envelope materials and designs in the early design stage (Natee et al., 2016). The initial costs of the building envelopes include their material costs and construction costs. The material costs differ with project location, building design, construction method, quantities of the materials purchased, and availability of materials. The construction costs signify the labour costs, machine costs, expenses, and other related costs for finalizing the project. These costs are easy to estimate in the preliminary design phases.

6.3.1.12 Maintenance costs (SEP2)

Maintenance is technical activities during the service life of the building envelope intended to preserve the envelope and its components in a condition where it can achieve its desired performs. Nonetheless, all buildings would at a point have maintenance costs since the envelope is exposed to the majority of wear and tear from the external environment. Building envelopes compromise different layers with different durability expectations and therefore require adequate maintenance to extend their usability as they get older (Kwon, Song, Ahn, Park, & Jang, 2020). Without adequate maintenance, the building envelopes will deteriorate faster and their service lives may be reduced. See **Figure 6-18**

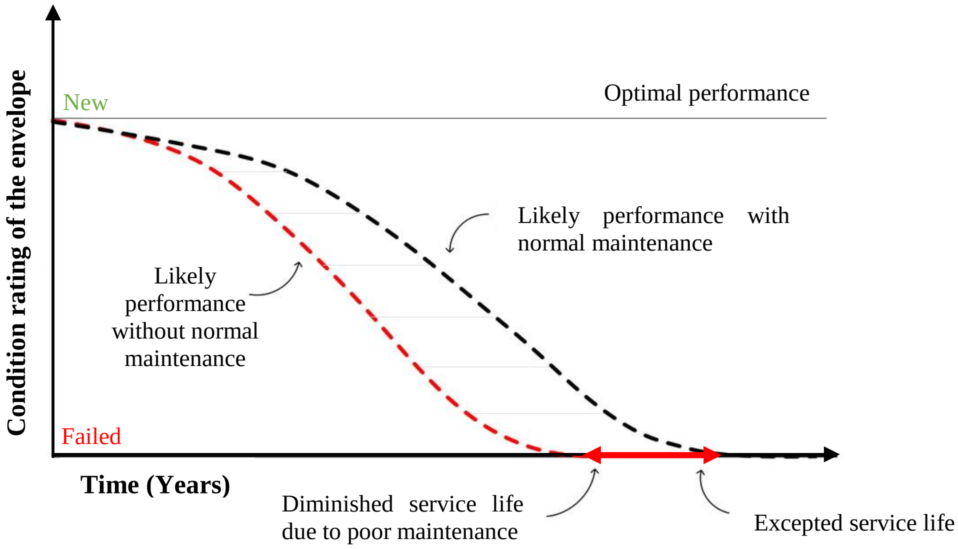


Figure 6-18: Impact of maintenance on the service life of a building envelope (roof)

Adapted from (Albrice & Branch, 2015)

Due to the interconnection features of the components (layers) integrated into building envelopes, maintenance or repair of one component can result in improvements in the overall system (National Research Council, 2012). The maintenance costs include activities to keep building envelopes in good working condition throughout the building lifespan. For examples washing of the windows or inspecting the sealants, roof drain cleaning, painting, and other small repairs. However, the designer must have proper knowledge of the use of specified materials and their maintenance periods and costs when integrating them into building envelopes and assemblies. Mostly, ensuring the quality and longevity of building envelopes is the key to reduce the likelihood of unexpected maintenance cost.

6.3.1.13 Replacement Costs (SEP3)

These include costs to replace or refurbish the building envelope components when they have reached the end of their service lifetimes. All building envelopes eventually require refurbishment over time. For instance, replacing deteriorated or aged flexible sealants, a replacement of the roof shingles every 15 to 25 years. The replacement becomes the most appropriate option when the components of the envelope reach a point at which they are not economically or functionally useful. However, assessing different building-envelope alternatives and timetabling their replacement periods could reduce maintenance costs, improve energy efficiency, and ensure an effective building shield.

The number and timing of capital replacements of building envelopes depend on the expected life of the envelopes and components. In particular, estimating reasonable replacement rounds of building envelopes is depends on gathering component-specific replacement periods from materials manufacturers or reviewing previous case studies (Jonghyeob Kim, Lee, Bender, & Hyun, 2018).

6.3.1.14 Demolition/deconstruction costs (SEP4)

Demolition costs are the cost of removing a component or structure at the end of its service life. These include costs of inspection, labours, transportation, disposing of material and any other associated costs (C. Liu, Lyle, & Langston, 2012). Generally, labour cost and waste disposal cost are the primary cost elements for demolition and deconstruction costs. The cost of demolition/deconstruction can vary based on the country and the typical wages in the region. Although several studies have shown the potential economic and environmental benefits of deconstruction, the deconstruction costs could be 17–25% higher than demolition costs (Dantata, Touran, & Wang, 2005). This is mainly because more labours will be hired to remove the building parts and also a long time is needed to salvage the components[81]. Generally, the disposal costs have a major share in the total traditional demolition costs, while the final cost is distributed between equipment, labours, transport, and disposal costs in the deconstruction approach (Coelho & De brito, 2013).

[81] According to Coelho and De brito (Coelho & De brito, 2013) , the necessary time to complete a traditional demolition for a 100 m2 standard housing unit would take 1 day while the required time to finish a deconstruction for the same unit is 6.5 days. Also, deconstruction requires as much as 6 times more labour than traditional demolition.

6.3.1.15 Locally available materials (SEP5)

Products that are manufactured and assembled locally using various local raw materials are considered regional products. Researching regionally available materials and products during the schematic design phase can facilitate the use of local materials. Using regionally extracted and manufactured materials can help lessen the costs compared to the cost of imported building materials; transportation resources and costs may also be reduced; at the same time, the local economy is supported (provide more jobs for the local community members). Moreover, rising fuel costs have significantly contributed to the high costs of building materials. In some cases, the transportation cost can be 20 to 25 times more than the cost of the material (Mukiibi, 2015). Therefore, the travel distance of the products, between the origin stores of the manufacturing plants (factory gate) to the construction site, should be taken into account from an early design phase.

6.3.1.16 Locally available Labour (SEP6)

The high employment of foreign labours (outsourcing) through prime contractors and intermediate subcontractors has become the trend in many countries which reduce the level of labour skill in the local construction industry, make the construction work temporary and insecure, and exclude many labours from the social security system (International Labour Organization, 2001).

Recently, construction stakeholders realize the importance of maximizing the employment of local labour in the project's construction and maintenance as an important step in the direction of sustainability (Peter, 2014). Labour constitutes a large share of the construction costs. Hence, local labour is used to achieve cost efficiency in the construction and support the local social context and local economy (the employment of local knowledge and the use of local facilities and services) (Hyde, Watson, Cheshire, & Thomson, 2007). In the long term, the employment of local labour will help in reducing the maintenance cost of the building envelopes by ensuring that local communities know how to maintain the building themselves.

On the other hand, Life cycle cost analysis (LCCA) of building envelopes has been considered in this research. LCCA helps in decision making for the selection of an alternative depend on net cost savings when all alternatives achieve an equal performance condition (Saleem et al., 2018). However, all costs accrued from all life stages of a building envelope are considered as potentially important to the decision (from construction to the end-use of the envelope). Undoubtedly, the balance between the cost of the building envelopes and their levels of performance will be of great significance in reaching the most cost-effective design of a building. **Table 6-21** gives an example of how alternative building envelopes might be ranked based on their average life cycle cost and availability of local materials and labours.

Alternative Building facades		Initial cost ($/m^2)	Total LCC cost ($/m^2)	Locally available materials are used	Locally available labours	Life cycle cost (LCC) states	Points
Layers from the most external to internal							
A	acrylic paint 4-mm Plaster 140-mm Brick 30-mm plaster Acrylic paint	283.64	1,434.20	√	√	Below Average	10
B	20-mm Granite clad- 70-mm Air 40-mm Plaster 140-mm Brick 30-mm Plaster Acrylic paint	435.10	1,487.87	√	√	Above Average	4
C	3-mm Aluminum clad- 70-mm Air 40-mm Plaster 140-mm Brick 30-mm Plaster Acrylic paint	395.06	1,445.45	√	×	Below Average	8

Table 6-21: Socio-economic performance and ranking of various facade assemblies

<u>6.3.1.17 Embodied energy (EE1)</u>

In recent years, the study and practice on embodied energy are getting more interest, since the proportion of embodied energy in life cycle energy use is rising as more high-performance energy-efficient buildings are being constructed. The embodied energy is significantly changed by the type of construction materials used, manufacturing efficiency, transportation mode and distance, the durability of the materials, and the applied construction techniques (Tuladhar & Yin, 2019).

Most of the recent studies are concentrating on levels of embodied energy in individual building materials rather than in the particular combination of materials as building assemblies (Watts, 2013). The use of embodied energy figures in construction should be cautious and must be considered in context. However, it is easier for decision-makers to compare the energy content per square meter of construction rather than looking at the energy content of all the individual materials used. Although the embodied energy of the structural components of the buildings represents the largest constituent in the total embodied energy, the embodied energy of the building envelope's materials (walls and roofs) represents a significant proportion of the total embodied energy (Dimoudi & Tompa, 2008; Utama & Gheewala, 2009; Yohanis & Norton, 2006).

As mentioned previously, the embodied energy of a building assembly can be reduced by using locally available, natural materials (ex. rammed earth walls) that are both durable and recyclable, with a design that combines components that are easy to recover and reuse. Also, the concept of prefabricated, modular and pre-assembly building envelopes (off-site construction[82]) can provide the means to a future construction that is low-embodied energy, flexible, adaptable and sustainable (Kamali & Hewage, 2016; Tavares, Lacerda, & Freire, 2019).

Every building is a complex grouping of many assemblies and materials, each of which adds to the building's total embodied energy. Embodied energy content changes significantly with various construction forms. In general, lightweight building construction assemblies such as timber frame is mostly lower in embodied energy than heavyweight construction. This is not necessarily the case if large amounts of light but high energy materials such as steel or aluminium (the higher embodied energy of the common building materials) are used. However, in some cases, low levels of embodied energy can be achieved by using mixed methods of lightweight and heavy-weight construction in a single building. **Table 6-22** displays some typical embodied energy figures derived for a range of selected construction systems.

[82] According to Kamali & Hewage (Kamali & Hewage, 2016) , there are four levels of off-site construction including component sub-assembly (such as windows and doors), non-volumetric pre-assembly (cladding panels), volumetric pre-assembly (toilets or bathroom pods) and complete modular building (modules that compose the whole building)

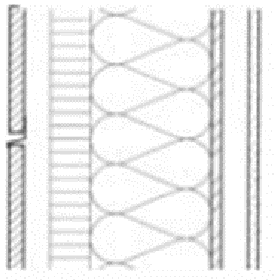
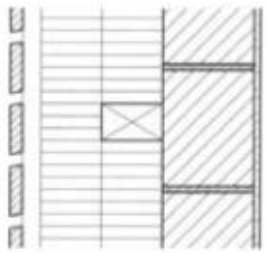
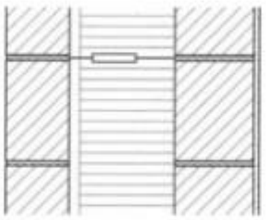
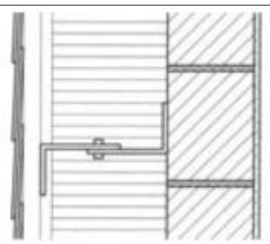
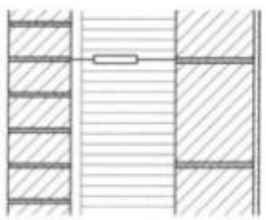
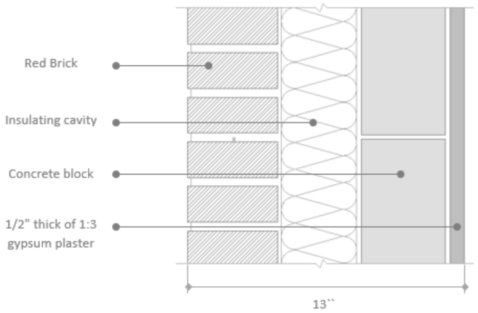
Assembly	Layers	Total thickness (mm)	Embodied energy (MJ/m^2)
	Inner lining Space for services Timber studs with 180 mm cellulose fibre insulation 60 mm wood fibreboard 3-ply core plywood, ventilation cavity, external cladding	330	490
	Plaster 150 mm calcium-silicate masonry 200 mm rock wool external insulation Solid timber sheathing, ventilation cavity, external cladding	410	560
	Plaster Double-leaf (120+150 mm) calcium-silicate masonry 180 mm rock wool cavity insulation	480	800
	Plaster 150 mm calcium-silicate masonry 200 mm rock wool external insulation Ventilation cavity, fibre-cement tiles	410	940
	Plaster 150 mm calcium-silicate masonry 180 mm rock wool cavity insulation 120 mm clay facing brickwork	500	1340

Table 6-22: Embodied energy in (MJ/m^2) for typical construction assemblies Adapted from (Josef, 2004)

The embodied energy involved in completing a typical building assembly per MJ/m^2 can be obtained if the embodied energy intensity and mass per kg/m^2 for each layer within the assembly are defined. **Table 6-23** gives an example of how to calculate the embodied energy of a traditional masonry cavity wall in MJ/m^2.



Building Assembly	Material/Layer	EE intensity MJ/kg	Mass kg/m^2	EE ($MJ/kg\times kg/m^2$)
(see drawing above)	Brick	3	123.5	371
	Insulation (fiberglass)	28	10	280
	Concrete block	0.75	176	132
	Plaster	1.8	36	65
	Paint MJ/m^2	21	-	21
Total embodied energy (MJ/m^2) =				**869**

Table 6-23: An example of embodied energy used in each layer within an insulated masonry cavity wall[83]

Note: Energy and carbon data adapted from (Hammond et al., 2011)

Furthermore, there is limited information to allow accurate comparisons of building envelope assemblies in terms of embodied energy. However, it has been noticed that the minimum process embodied energy requirement varies considerably among construction assemblies ranging from less than 200 MJ/m^2 (e.g. straw bale wall assembly) to more than 1000 MJ/m^2 (e.g. traditional masonry insulated cavity wall). Therefore, based on these figures, a weighting scale to properly characterize the embodied energy of various building assemblies have been proposed to evaluate the total impact of a given system. This ranking scale is presented as a simple demonstration of the theoretical aspects behind embodied energy. (See **Figure 6-19**)

Embodied energy (MJ/m^2)	>1000	≥800 and <1000	≥600 and <800	≥400 and <600	≥200 and <400	<200
Points	0	2	4	6	8	10

Figure 6-19: The ranking scale of building assemblies based on their embodied energy intensities

The specification of construction assemblies might be changed so as to reduce the amount of embodied energy but still work well to achieve other functional performances such as thermal mass values and footprint-related issues to be minimized.

[83] Although materials like damp-proof course or stainless ties (connect brick and block in the wall) have a high embodied energy-intensity, their overall share in the final embodied energy is very low as they normally used in low quantity. Therefore, they did not included in the EE calculation.

6.3.1.18 Thermal resistance (EE2)

The thermal performance of building envelopes has a great effect on sustaining indoor environmental qualities and is critical in achieving an energy-efficient design. It is one of the factors which govern the needs of cooling or heating load for indoor thermal comfort[84]. However, choosing an appropriate building envelope is one of the most effective ways to manage heat flows, avoid extreme building energy consumption, and keep a comfortable temperature for inhabitants (Natephra et al., 2018). The building designer is responsible for making sure that the building envelope is energy efficient and fulfils the code and climate requirements. To improve the thermal performance of the buildings, the building envelopes' thermal characteristics have been the first to be pointed. This should include the opaque envelope structure (walls and roofs) and transparent envelope (exterior windows).

The selection of energy-efficient building envelopes must be handled based on the requirements of the local climate parameters of each site as it is not possible to bring recommendations of solution that can obtain energy efficiency for all buildings. Climate plays a significant role in building energy demand (Yuang Guo & Bart, 2020) and several climate classification systems[85] are in use for different purposes. Therefore, to develop a simple and universal ranking system, four basic types of climates have been considered based on the nature of the human thermal problem in a particular location. These include cold climates, hot-dry climates, warm-humid climates, and temperate (moderate) climates. The climate zones are defined based on heating degree days, cooling degree days, solar radiation, and humidity levels.

The Heating degree days (HDD) and Cooling degree days (CDD) are a measure of how cold or hot the weather (temperature) was on a given day or during days. They are fundamental factors to assess the heating and cooling required for different regions. A high number of degree days generally contribute to a higher level of energy consumption for heating or cooling. Also, solar radiation has a major role in determining the indoor thermal comfort level and the amount of heat transfer through building envelopes (indoor

[84] ASHRAE standard 55 (ASHRAE Standard 55, 2004) and ISO standard 7730 (ISO, 2005) define thermal comfort as the condition of mind which expresses satisfaction with the thermal environment. Mostly, once the majority of people felt the range of climatic conditions where they are comfortable with the heat or cold, they have reached the comfort zone (Mirrahimi et al., 2016).

[85] The Most widely used scheme is the Köppen climate classification. It divides climates into five main climate group while distinguishing some 25 climate types. The five main groups include: A (tropical); B (dry); C (temperate); D (continental); and E (polar).

cooling load in summer). Likewise, the humidity level has a significant impact on indoor thermal comfort. Generally, the humidity comfort zone is considered in between 30% and 70% RH. **Figure 6-20** shows the main four climatic zones.

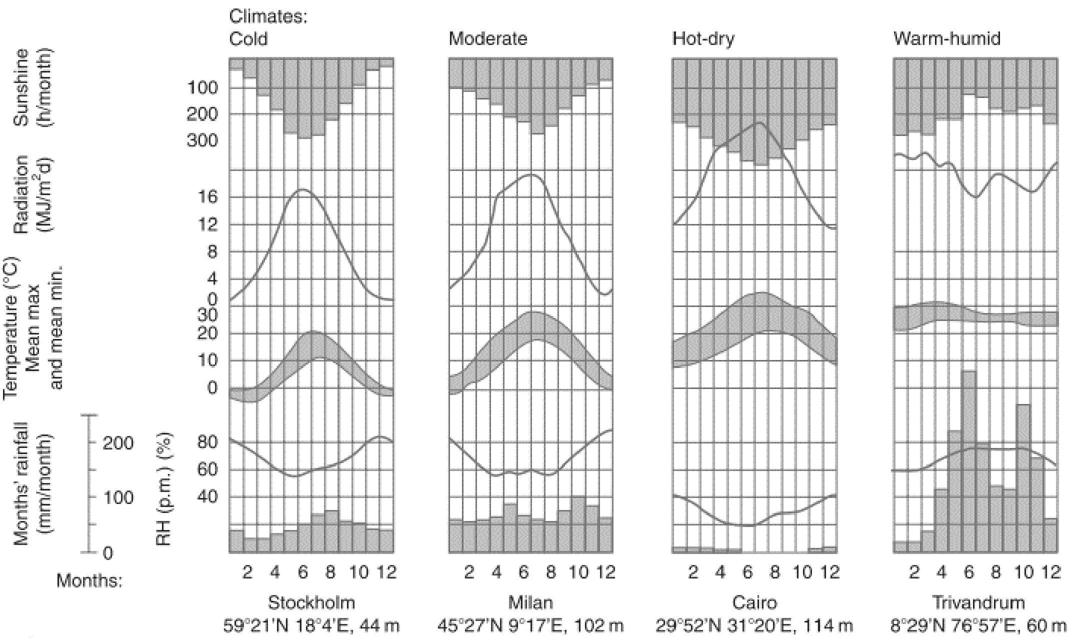


Figure 6-20: Four major climatic zones of the world

Adapted from (Szokolay, 2008)

I) Hot-dry climates:

The main problem is overheating and the air is dry and there is a large diurnal temperature variation. In this climate, almost half the urban peak load of energy consumption is utilized to fulfil air-conditioning cooling loads in the summer period (Dabaieh, Wanas, Hegazy, & Johansson, 2015). In this climate, three parameters are affecting the thermal behaviour of building envelopes including thermal mass, thermal insulation and solar reflectance index (Alhamdani & Ahmed, 1987).

Thermal mass is useful in a typical hot-dry climate with a large diurnal variation and low relative humidity, where the temperature varies over the daily cycle between too high and too cold (Reilly & Kinnane, 2017). It can be used effectively to absorb daytime heat gains to keep the indoor temperature at a moderate level (reducing cooling load) and release the heat during night time (reducing heating load) (L. Yang, Fu, He, He, & Liu, 2020).

The time delay as a result of the thermal mass is known as a time lag, and the reduction in cyclical temperature on the internal side of the building envelope in compared to the external side is identifies as a decrement factor (X. Jin, Zhang, Cao, & Wang, 2012). Show **Figure 6-21**

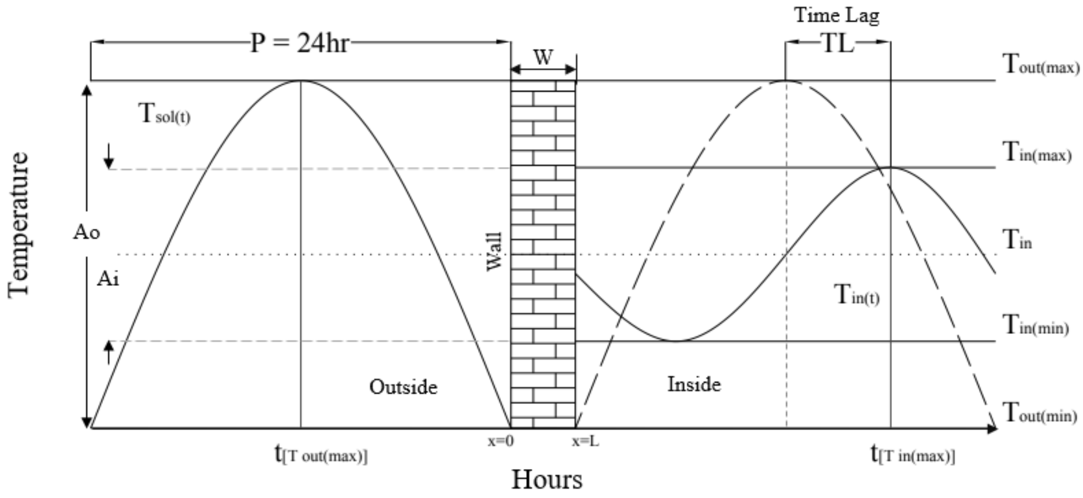


Figure 6-21: The schematic representation of time lag and decrement factor

The time lag (ϕ) can be defined by the following equation (Asan, 1998; Fathipour & Hadidi, 2017; Toure et al., 2019):

$$\phi = t_{Tin,max} - t_{Tout,max} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(32)$$

Where: $t_{Tin,\ max}$ and $t_{Tout,\ max}$ represent the time in hours when internal and external surface temperatures of the walls are at their maximums.

As shown in the above Figure, the temperature of the heatwave outside which reaches the external surface of the envelope is symbolized by Tsol(t); named sol–air temperature. The temperature of the heatwave which enters the inside via the external surface of the wall is remarked by Tin(t). Minimum and maximum values of the temperature profile at the inner surface of the wall during the specified period is remarked as Tin(min) and Tin(max); the amplitude of this profile is symbolized by Ai. Minimum and maximum values of the outdoor temperature profile are remarked by Tout(min) and Tout(max); The amplitude of this temperature profile is symbolized by Ao. P is the period of the heatwave. Referring to the above-mentioned parameters, the decrement factor (f) can be calculated by the following equation:

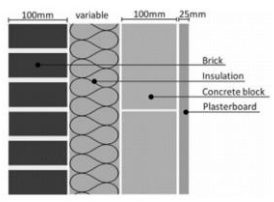
$$f = \frac{A_i}{A_o} = \frac{Tin^{max} - Tin^{min}}{Tout^{max} - Tout^{min}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(33)$$

Following the above, ideal materials for thermal mass are those materials that have a high specific heat capacity and high density. In general, heavyweight construction materials such as brick, stone and concrete have these properties. Furthermore, thermal retention capacity (kJ/m^2.K) is the most important factor to consider when discussing thermal mass in buildings. It is a measure response characteristics of the construction. It is linked directly with the density and specific heat capacity and the thickness of building materials (the higher the figure, the more heat is needed to increase the volume of a material to a higher temperature, and the more warmth it emits when cooling[86]) (Volhard, 2016). For a building envelope constructed of multiple materials, the total heat capacity is determined as the sum of the heat capacities of the individual components[87].

The increase of the thermal retention capacity and the thickness of the building envelope increases the time lag[88] and decreases the decrement factor (X. Jin et al., 2012). However, it is not beneficial to apply thermal mass if the time lag is too long. For example, if the time lag of a wall exceeded 12 hours, heat will still transfer to the internal spaces which can lead to overheating. A delay of between 8 and 12 hours might be considered optimum in most cases (Sajjadian, 2017). The heat capacity (thermal mass parameter) can vary significantly from 55 kJ/m^2.K for a lightweight timber frame construction to 500 kJ/m^2.K for solid masonry construction (heavyweight). **Table 6-24** shows the thermal storage capacity of a masonry wall construction. The heat capacity for a construction element (K) can be calculated from the following equation:

$$K = 10^{-6} \times \sum(dj\ rj\ cj) \qquad (34)$$

Where: dj is the thickness of a layer (mm); rj is the density of a layer (kg/m^3); cj is the specific heat capacity of a layer (J/kg·K).



Assembly	Materials/ layers	W (m)	Density Kg/m^3	Specific heat capacity (J/kg K)	Thermal retention capacity (kJ/m^2 K)
	Brick	0.10	1700	800	136
	Insulation	0.059	24	1400	2
	Concrete block	0.10	2300	1000	230
	Plasterboard	0.025	950	840	20
Total		0.2615			**388**

Table 6-24: An example of thermal retention capacity of a wall assembly

Adapted from (Aldawi, Date, Alam, Khan, & Alghamdi, 2013)

[86] Commonly, it is more suitable to select high storage capacity assemblies for buildings and spaces designed to be used for a long periods of time.

[87] Lightweight materials such as insulation do not have a significant effect on heat capacity of the building envelopes and are often discounted when determining the overall heat capacity.

[88] As a general notice, the time lag decreases with the increase of the thermal conductivity and U-value of the building materials and assemblies while the decrement factor increases.

Moreover, the introduction of sustainability concepts in modern eras demands the use of thermal insulation in the building's walls and roofs to reduce heat gain and heat loss (Osman & Sevinc, 2019). Previous research showed that thermal bridges will be eliminated and a significant cooling energy reduction could be achieved when locating thermal insulation within the outer side of the building envelopes (Sajjadian, 2017; M. A. E. Saleh, 1990). The external application of thermal insulation can increase the time lag and reduce cooling energy consumption (Vijayalakshmi, Natarajan, & Shanmugasundaram, 2006).

Furthermore, several studies have proved a significant difference in heat gain if light colours are used instead of dark colours. In general, cool materials are required to have a solar reflectance higher than 0.65 to perform well (Luisa F.Cabeza et al., 2019). Also, the solar reflectance index (SRI) is used to measure the ability of a surface to stay cool in the sun by reflecting solar radiation and emitting thermal radiation (Casini, 2016).

II) Hot-humid climates:

In hot-humid climates the overheating is not as great as in hot-dry climates, nevertheless, the diurnal temperature variation is intensified by high humidity, limiting the evaporation capability and the diurnal temperature is small. The air temperature and relative humidity are the critical factors in defining the comfort level in this climate. Commonly, lightweight construction with low thermal mass (ex. Timber and Weatherboard) is suitable for hot and humid climate because it helps to reduce heat storage (lose heat at a faster rate) which can have negative effects on indoor temperatures at night[89] (Harvey, 2006; Sudhakar, Winderla, & Priya, 2019).

In a hot-humid climate, low mass construction is desired for saving energy and providing thermal comfort for the building's occupants (Mirrahimi et al., 2016; Triana, Vecchi, & Lamberts, 2020). Passive cooling in this climate is typically more efficient in lightweight envelope design (low ability to store heat). Also, highly reflective envelope surfaces with low solar absorption (Ex. materials with high solar reflectance and high infrared emittance) are preferred to reduce cooling energy (Sudhakar et al., 2019). Furthermore, exterior thermal insulation (in a range from 0.025 to 0.06m) can reduce both annual cooling energy and peak cooling load (Hassan & Al-ashwal, 2015; H. Wu, Wang, Liu, & Wang, 2017).

[89] Lightweight construction reacts to temperature changes more rapidly (for example it takes less energy to get the building to a comfortable temperature).

III) Cold Climates

In cold climates, the main problem is the lack of heat (underheating), so maximizing building envelope insulation to keep warm air inside the building is essential to provide adequate thermal comfort and to minimize heating load (Goia, Time, & Gustavsen, 2015). The concept of thermal transmittance (U-value or heat transfer coefficient) has become the main parameter in evaluating the thermal property of the building envelopes to establish the steady-state thermal transfer performance.

According to Abdul Nasir and Hassan (2020), thermal transmittance can be defined as the amount of heat energy that flows through a certain element per unit area and time, and it is measured in watts per square meter per kelvin ($W/(m^2.K)$). The lower the U-value, the lower the heat transfer between the internal and external environments. Generally, in the cold region, a heat transfer coefficient of fewer than 0.5 $W/(m^2·K)$ must be used in most locations of this climate (G. Feng, Sha, & Xu, 2016). **Table 6-25** gives an example of the calculation of the overall thermal transmittance of a wall.

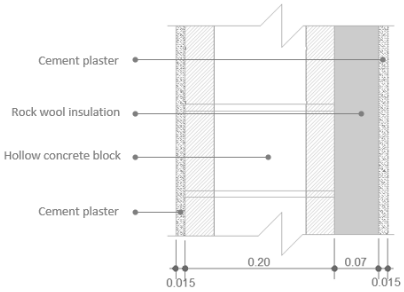
Building Assembly	Assembly layers	Layer width (m)	Thermal conductivity (W/m.K)	Thermal resistance (m^2.K/W)
	Outside thermal resistance			0.04
	Cement plaster	0.015	0.72	0.02
	Rock wool	0.07	0.042	1.67
	Hollow concrete block	0.20	0.614	0.33
	Cement plaster	0.015	0.72	0.02
	Inside thermal resistance			0.13
Total thermal resistance				2.21
Total heat transfer coefficient U = 1 / R = 1/2.21 = **0.45 W/m².K**				

Table 6-25: Calculation of the heat transfer coefficient of a wall

Furthermore, exterior insulation is required to improve the thermal efficiency of the building envelopes and also to help manage moisture problems due to air leakage (Al-Turki & Zaki, 1991; Ozel, 2014; J. Straube, 2011). Although the application of external building materials with high SRI is recommended widely without much regard for climate or project limitations, some studies argued that building envelopes with low SRI are preferred to lower the annual air-conditioning loads in cold climates (Shi & Zhang, 2011). According to Hosseini and Akbari (2016) and Pisello et al.(2015), negligible wintertime heating penalties for cool materials (roof and façade) have been noticed in cold climates. Moreover, the use of high thermal mass construction to gain winter solar radiation and to restrict heat loss through building envelopes is identical in this climate especially for the continuously applied buildings (Carlos, 2017; Rajasekar, Thakur, & Zeleke, 2020). Still, in a region with lower solar gains, the thermal mass showed several benefits concerning indoor thermal comfort and energy consumptions (Andersson, Engström, & Lindström, 2012).

IV) Temperate climates (Moderate)

In temperate climates, there is a small seasonal variation between underheating and overheating, but neither is very severe. However, the U-value is less restricted than in a cold climate, in order of 0.7 W/ (m2 ·K) or less (Szokolay, 2008). Additionally, external building materials with high SRI are recommended for use in this climate (Akbari, Levinson, Rosenfeld, & Elliot, 2009). Conversely, other studies claimed that building envelopes with medium reflectance and low longwave emissivity can fit the energy-saving requirements in temperate climates (Shi & Zhang, 2011; Tiago, Margarida, Vítor, João, & Adélio, 2020).

On the other hand, thermally insulated high mass building envelopes are desirable for this climate, because they facilitate proper time lag by storing solar thermal energy during the day and emit it in the night when the external temperatures decrease (Košir, 2019). Furthermore, thermochromic materials are considered a suitable option for moderate climates because they have the ability to change the absorption of solar radiation dynamically according to the external weather conditions, therefore, they have a huge capacity in reducing, simultaneously, the cooling and heating demand in buildings (Yuxuan, Yunyun, Jianrong, & Xiaoqiang, 2020). Moreover, placing an insulation layer on the external side of building envelopes can present high performance in terms of heating and cooling energy use, as well as global thermal comfort (Q. Jin, Favoino, & Overend, 2017).

It is worth noting that, thermal mass, thermal transmittance and solar reflectance are not the only parameters that determine the building envelopes thermal behaviour. Other parameters such as the design configurations, building orientation, and external shading should be considered as a whole for optimizing the building thermal reaction and energy performance. **Table 6-26** demonstrates how building envelopes can be ranked in terms of their thermal resistance performance.

Hot-dry climate			
A large thermal mass capacity (≥250 kJ/m^2.K)	External insulation is used on the outside of the building envelope (0.05-0.10 m)	High SRI surfaces (≥65%)	Points
●	●	●	10
●	●	×	8
●	×	●	6
×	●	●	4
●	×	×	2
Other options			0
Hot-humid climate			
Lightweight construction with low thermal mass(<250 kJ/m^2.K)	External insulation is used on the outside of the building envelope (0.025-0.06 m)	High SRI surfaces (≥65%)	Points
●	●	●	10
●	●	×	8
●	×	●	6
×	●	●	4
●	×	×	2
Other options			0
Cold climate			
High insulation level (less than 0.5 W/(m^2·K) is used	External insulation is used on the outside of the building envelope	A large thermal mass capacity (≥250 kJ/m^2.K**)**	Points
●	●	●	10
●	●	×	8
●	×	●	6
×	●	●	4
●	×	×	2
Other options			0
Temperate climate			
The insulation level of fewer than 0.7 W/(m2·K) is used	External insulation is used on the outside of the building envelope	High SRI surfaces (≥65%)/ thermochromic materials	Points
●	●	●	10
●	●	×	8
●	×	●	6
×	●	●	4
●	×	×	2
Other options			0

Table 6-26: A point scale to rank building envelopes based on their thermal resistance performance in various climates

6.3.1.19 Solar Heat Gain Coefficient (SHGC) (EE3)

The energy efficiency of the transparent envelopes is broadly defined by solar heat gain coefficient (SHGC) and thermal transmittance (U-factor). The major energy-performance characteristic of windows is the ability to control solar heat gain through glazing. The source of solar heat gain is the direct and diffuse radiation coming from the sun and the sky. The Solar heat gain is influenced by the glazing type, the number of panes, glass coatings, shading from the frame as well as the ratio of glazing and frame (Mempouo, Cooper, & Riffat, 2010). See **Figure 6-22**

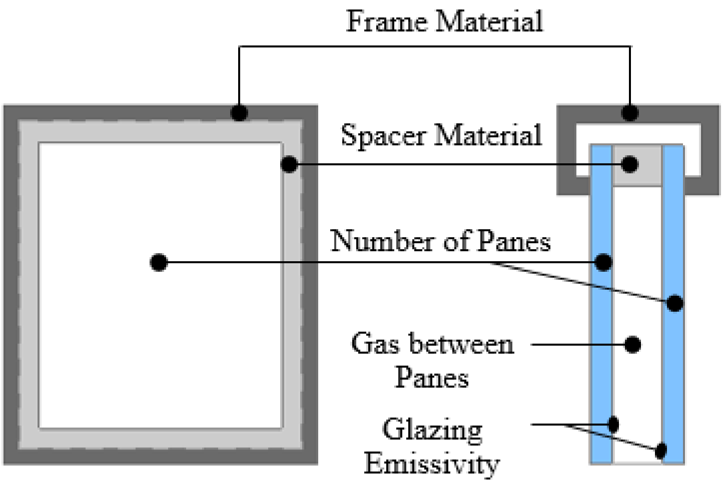


Figure 6-22: Factors affecting the energy performance of windows

The solar heat gain coefficient (SHGC) is the ratio of the solar heat gain that is transmitted through the window area to the incident solar radiation (including window frames). The SHGC is expressed as a number from 0 to 1; the lower the SHGC of a window, the less solar heat it transmits and the greater its shading ability. In real construction practices, products typically range between 0.2 and 0.9, for instance, SHGC is above 70% for uncoated clear glass to less than 25% for highly reflective coatings on tinted glass (T.Grondzik, G.Kwok, Stein, & S.Reynolds, 2010).

Generally, windows with low SHGC values are required in buildings with high air-conditioning loads while windows with high SHGC values are suitable in buildings where passive solar heating is needed (Bhatia, Sangireddy, & Garg, 2019; Ihara, Gustavsen, & Jelle, 2015). In cooling dominate climate and in situations where air-conditioning costs during warm months can become high (temperate climate), windows with an SHGC of less than 0.40 can be beneficial as blocking solar heat is useful during the summer season. Furthermore, in heating dominant climates, a high solar heat gain coefficient (SHGC value greater than 0.40) is suited for heating energy reduction and windows with such properties are considered the best choice for passive solar design projects (Fine Homebuilding, 1999). **Figure 6-23** shows a ranking scale of building windows based on their SHGC value.

Hot-dry/Hot-Humid climates / in moderate climate (both heating and cooling are required)

SHGC	>0.45	>0.40 and ≤0.45	>0.35 and ≤0.40	>0.3 and ≤0.35	>0.25 and ≤0.30	≤0.25
Points	0	2	4	6	8	10

Cold-climates

SHGC	<0.35	≥0.35 and <0.40	≥0.40 and <0.45	≥0.45 and <0.50	≥0.50 and <0.55	≥0.55
Points	0	2	4	6	8	10

Figure 6-23: The ranking scale of windows based on their SHGC in different climates

6.3.1.20 Thermal transmittance of windows (EE4)

Thermal transmittance is quantifying the rate of loss of non-solar heat of a window assembly and can be expressed as U-factor. The thermal transmittance value of the windows is six times higher than those of other components of building envelopes, and around 20-50% of the building's energy is lost through windows (Gustavsen, Grynninga, Arasteh, Jelle, & Goudey, 2011; J. W. Lee, Jung, Park, Lee, & Yoon, 2013). Therefore, the design and the selection of a proper window system can effectively help in reducing the energy consumption of the buildings. Window and frame assemblies are composed of several components which conduct heat differently at different points.

The overall thermal transmittance of the window is the average between the thermal transmittance of the frame and the glass. Currently, the best glazing units can have a U-factor as low as 0.3 ($W/m^2.K$), whereas the best window frames can have a U-factor as low as 0.6 ($W/m^2.K$). The lower U-factor means less heat will be transfer through the window. For instance, a double-pane window with a U-factor of 0.30 $W/m^2.K$ or lower will work well to save energy loss through it (Gustavsen et al., 2011).

In considering a window frame, selecting window frame materials can also have a major impact on the thermal transmittance and energy efficiency of the window unit. A sash and window frame can represent 10–30 % of the total area of the window unit (Asif, Muneer, & Kubie, 2005). A typical window can have a U-value ranging from 2 $W/m^2.K$ to 4.5 $W/m^2.K$, while it fluctuates in a range from 0.8 $W/m^2.K$ to 1.5 $W/m^2.K$ in high-performance windows (Paulos & Berardi, 2020). Typically, Low-emittance coatings and gas fills between panes are used in an attempt to further decrease U-factors and provide more energy-efficient products. Double-glazing window is widely used in cooling-dominant regions, while double-or triple-glazing with vinyl frames are used in heating-dominant zones (He, Ng, Hossain, & Skitmore, 2019). (See **Table 6-27**)

ID	**Glazing Type**	**Frame Type**	**U-factor** W/m$^{2\cdot}$ K	**SHGC**
1	Single, clear	Metal	1.29	0.73
2	Double, clear	Metal	0.83	0.65
3	Single clear	Vinyl	5.62	0.82
4	Double clear	Vinyl	3.07	0.70
5	Double, tint	Metal	0.83	0.54
6	Double, Low-E[90], high SHGC, argon	Metal	0.65	0.58
7	Double, Low-E, medium SHGC, argon	Metal	0.64	0.38
8	Double, Low-E, low SHGC, argon	Metal	0.63	0.26
9	Double, low-solar-gain Low-E	Aluminum	0.59	0.37
10	Double, low-solar-gain Low-E	Wood/wood clad	0.34	0.30
11	Double, low-solar-gain Low-E	Insulated fiberglass	0.26	0.39
12	Double, Low-E, high SHGC, argon, improved	Improved nonmetal[91]	0.29	0.50
13	Double, Low-E, medium SHGC, argon, improved	Improved nonmetal	0.28	0.31
14	Double, Low-E, low SHGC, argon, improved	Improved nonmetal	0.27	0.20
15	Triple, Low-E, high SHGC, argon, improved	Improved nonmetal	0.20	0.41
16	Triple, Low-E, medium SHGC, argon, improved	Improved nonmetal	0.19	0.28
17	Triple, Low-E, low SHGC, argon, improved	Improved nonmetal	0.19	0.18

Table 6-27: Properties of a generic set of windows

Adapted from (Carmody & Haglund, 2012; Mempouo et al., 2010)

[90] low-e window is a window coated with a thin film layer that exhibits low thermal emittance and high solar transmittance
[91] Non-metallic frames have better thermal characteristics than the metallic frames.

The thermal transmittance (U-value) is a very important criterion for the windows especially in heating-dominated climates, as the heat transferred out is considerably higher than the heat coming into space (Banihashemi, Golizadeh, Reza Hosseini, & Shakouri, 2015; J. W. Lee et al., 2013; Y. Tan et al., 2020). Generally, heating bills can help determine the importance of U-factors in other climates (mixed-climates). Higher heating bills indicate the importance of windows with a lower U-factor for added energy efficiency. In colder climates (heating-dominated), windows with a U-factor less than or equal to 0.30 $W/m^2.K$ are preferable (Carmody & Haglund, 2012). Also, windows with low U-factor are favoured in temperate climates (with both heating and cooling seasons) to maximize energy savings. See **Figure 6-24**

Cold Climates/ Temperate climates

U-factor ($W/m^2.K$)	$\geq$0.50	$\geq$0.45 and <0.50	$\geq$0.40 and <0.45	$\geq$0.35 and <0.40	$\geq$0.30 and <0.35	$\leq$0.30
Points	0	2	4	6	8	10

Figure 6-24: The ranking scale of windows based on their U-factor

6.3.1.21 Embodied Water (EW1)

As climate change became a concern, the construction industry encouraged the measurement of embodied water of building materials. Embodied water of products may vary since the product may differ in different parts of the world. Some building materials and products entail large amounts of water during mining, production and construction (Meg, 2008). For instance, water is used for several purposes including mixing and shaping in ceramic production; cooling, cleaning and batch humidification in the glass industry; resin preparation and spraying in wood manufacturing; and cooling, gas cleaning, scale breaking and washing operations in steel production. According to MacIeira and Mendonça (2016), apply dry construction systems can contribute significantly to the reduction of water demand in buildings.

The construction industry consumes 16% of the water in the world (Heravi & Abdolvand, 2019). Hence, the selection of materials can have a great impact on a building's water demand during the construction phase. Up to date, few studies have been considered the embodied water of building envelopes and construction. This research part proposes a ranking method for the selection of building envelope systems in terms of water used to establish a better understanding of the subjects and showing its implication. The total embodied water of a building envelope can be obtained by multiplying each product quantity by the corresponding embodied water coefficient. (See **Table 6-28**)

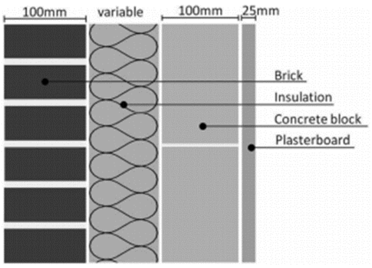
Assembly	Materials/ layers	Unit	The quantity used (per m^2)	EW coefficient KL/Unit	EW in the layer (KL)
	Brick	m^2	50	0.71	35.5
	Insulation	m^2	1	0.69	0.69
	Concrete block	m^2	10	2.67	26.7
	Plasterboard	m^2	1	0.63	0.63
	Mortar	m^3	0.021	10.55	0.22
Total EW of the assembly per m^2 =					63.74

Table 6-28: An example of total embodied water of a masonry wall

Due to the synergy between embodied water, embodied energy, and embodied energy, many of the strategies for optimizing embodied energy and embodied carbon are also applied for minimizing the embodied water of the construction assemblies (Lupíšek, Vaculíková, Mancík, Hodková, & Ržika, 2015). Mainly, reducing the number of needed materials and substituting the traditional materials and technologies with lower environmental impacts alternatives. **Table 6-29** gives a point scale to select building materials based on several factors/criteria to minimize the embodied water from an early design stage.

Low-embodied water coefficient materials are used (< 1 KL/unit)	Dry/ Mechanical fixations are used instead of wet-fixations	Higher recycled content assembly (≥50%)	Assembly can be fully or partially disassembled /Assembly components can be reused or recycled	Durable assembly (≥25 years)	Points
●	●	●	●	●	10
At least 4 of the above criteria are included					8
3 of the above criteria are included					6
2 of the above criteria are included					4
1 of the above criteria are included					2
None of the above					0

Table 6-29: Ranking scale for the selection of low-embodied water assemblies

6.4 Chapter Summary

The building envelope is a mix of construction layers with different properties, each intended to serve one or multiple functions within the building enclosure. It is essential for building envelopes to provide building occupants with a comfortable and safe environment, therefore, a building envelope must be able to tolerate rainwater and moisture penetration, sound, heat gain and loss, fire, and pollution, while providing security, safety, thermal and visual comfort. Vitally, these factors can be restrained by selecting an appropriate building envelope, and all of these factors should be combined in a balanced approach from an early design stage.

The decision to select an envelope system among alternatives is difficult because it is a multi-criteria problem involving environmental, economic, social, and other factors. Therefore, a comprehensive list of criteria for the assessment of the building envelope materials and designs based on extensive literature reviews were established in this chapter. Generally, some of these criteria are governed by building regulations, codes, etc., and others are freely varied inside a certain limit. Although the criteria are selected to cover all important characteristics of a decision problem, they have been lessened as much as possible in order to lower the use of manpower, time and cost.

The chapter highlights the importance of including all aspects that are important for decision making and for achieving sustainability in building. This approach supports screening, prioritizing, ranking, scoring, and selecting alternatives. The framework is based on collecting systematic data and technical information on building materials from the material's manufacturers to make the final decisions.

The findings of this chapter recommended that it is necessary to know the appropriate criteria and their limit values, which, if not exceeded, governs the achievement of the sustainable design. In conclusion, the proposed framework will motivate decision-makers to adopt a new system based on multi-objective to optimize building envelopes choices and evaluate their feasibility. It will contribute to offering a roadmap for transforming existing building envelopes into sustainable built systems. However, the framework should be further reviewed by experts and tested in real construction projects for validation.

CHAPTER 7: CASE STUDIES

7. CHAPTER SEVEN: CASE STUDIES

7.1 Introduction

The overall aim of this chapter is to ensure that the relevant research questions are explored through a variety of perspectives allowing for multiple facets of the research problem to be revealed and understood. This chapter consists of case studies of a range of individual building materials and assemblies in an attempt to show how the proposed framework presented in the prior chapters can be applied in the material selection stage in real construction practice. According to Bill Gillham (2000) and Yin (2003), case studies have formerly been accepted as a significant and acceptable research methodology in many research fields including planning, design and construction, economic and political science. They grant a practical analysis into a realistic context of research work.

In this part, the case studies are mainly examined to simplify the complex material selection concept, generate hypotheses, improve analytical thinking, validate the proposed tool and methods in real-world applications, and also give more insights regarding the research topic. Each case study shows the critical factors (criteria) which have a major contribution to the overall sustainability index of building materials. The case studies were selected for their applicability to the overall aim of the research. Most of the case studies information presented herein obtained from questionnaires, building materials manufacturers' websites and catalogues, and peer-reviewed studies.

7.1.1 Case study I

In this case study, the overall sustainability index of ALPOLIC 405 / fr (4mm, M9010 White (G30)) will be determined to see its role in the achievement of sustainable development goals (SDGs) when integrated into the facade of an office building in Tokyo-Japan. ALPOLIC is the brand name of the Aluminium Composite Material (ACM) produced by Mitsubishi Chemical Corporation for over 40 years in Japan. It often used as an alternative to solid aluminium panels (and other metal plates) because it could achieve equivalent rigidity using only one-third to one-fourth the amount of aluminium. For instance, the 4mm ALPOLIC panel is equivalent to a 3.3mm thick solid aluminium sheet. The material is a three-layer structure composed of two sheets of aluminium for the surfaces and resin for the core material. It has been universally used in the construction industry as a facade material in many types of buildings (ex. office buildings, commercial facilities and infrastructure projects) due to its various characteristics. See **Table 7-1**

Name	Plate thickness	specific gravity	weight	Thermal conductivity	Coefficient of linear expansion	Flexural modulus	Tensile strength
	mm	---	kg / m²	W / m ・ K	X10^{-6}.1/K	N / mm²	N / mm²
405 / fr	4	1.90	7.6	0.85	21-27	39,800	46

Table 7-1: General properties of ALPOLIC 405/fr

ALPOLIC is a lightweight material with excellent flatness and high rigidity (because of the sandwich structure of aluminium and resin), great adaptability, and ease of fabrication and selection of various colours and finishes. These features assist architects and designers in achieving almost any design exterior outlook. However, the degree of sustainability of this material has never been studied before. This architectural exterior panel has been selected because it has been used in different construction projects including some of the most famous landmarks in Tokyo. See **Table 7-2**

The composition of ALPOLIC 405/ fr is (from the outermost surface) baking fluororesin coating finish (average 30 microns which boast high weather resistance even in harsh environments including coastal areas) / aluminium (0.5 mm) / mineral filled fire resistant core material (aluminium hydroxide highly filled resin, 3.0 mm) / Aluminum (0.5mm) / Polyester coating finish (average 5 microns), total thickness 4.0mm (has been used as the standard overall thickness). The maximum dimensions 2.0 (W) x 7.2 (L) m. See **Figure 7-1**

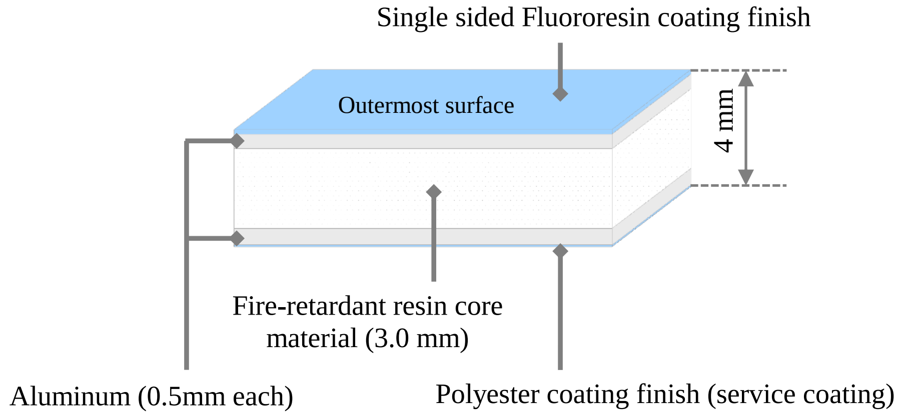


Figure 7-1: The composition of ALPOLIC 405 / fr exterior panel

7.1.1.1 Resource and Material Efficiency Index

ALPOLIC 405 fr is capable of reuse, but it is more likely to be recycled. Both aluminium and the core material are recovered for recycling at the end of the material lifetime. Also, Aluminium alloy 3105-H14 is most commonly used as a standard Aluminum type in

ALPOLIC which holds a higher percentage of recycled content. Aluminium scrap could be infinitely recycled without any loss of value or properties (European Aluminium, 2015). According to the International Aluminium Institute (2020), 75% of all the Aluminium ever produced is still in use today. Generally, scraps from ALPOLIC production plants and other scarps from the domestic market (customers) are collected, sorted and reprocessed in specific recycling plants before utilizing them once again in the ALPOLIC manufacturing plants. See **Figure 7-2**

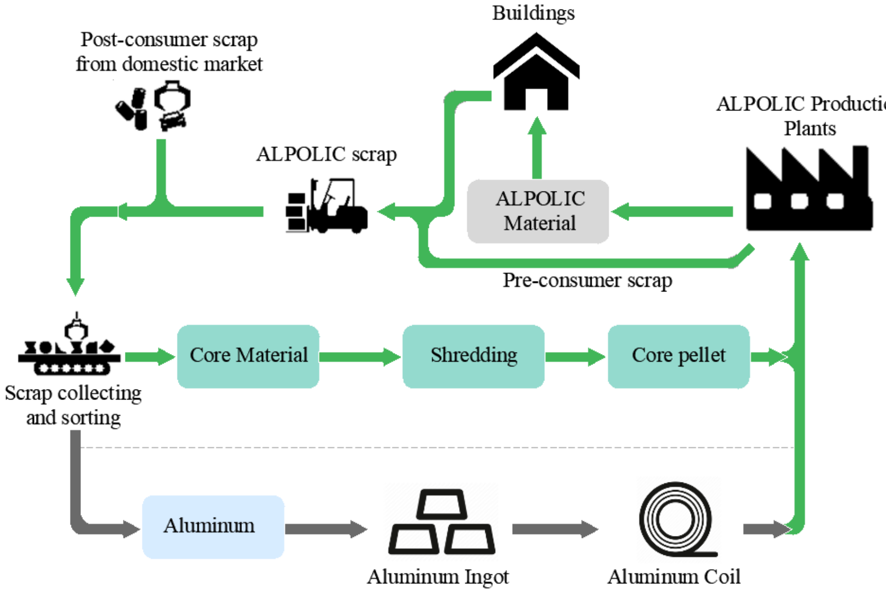
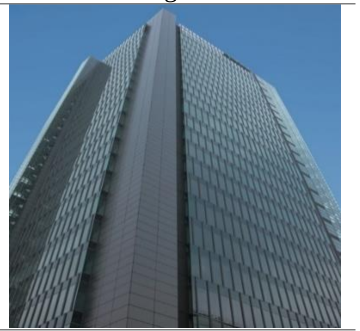
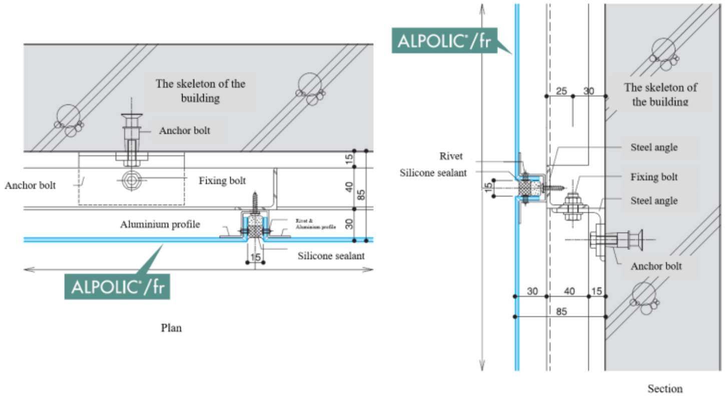


Figure 7-2: The lifecycle diagram of ALPOLIC material

As a result of the sandwich structure, ALPOLIC 405/fr needs roughly half the amount of aluminium to achieve the same strength as solid aluminium panels, make it more resource-efficient than solid aluminium panels. The expected lifetime (durability) of ALPOLIC 405/fr achieves a reference life of more than 30 years and up to 20 years warranty is normally given by the manufacturer. The guarantee is directly linked to the performance of the applied surface coating. The coating can help ALPOLIC to resist corrosion and withstand issues such as wear and exposure to water and also improve the aesthetic appearance. The Lumiflon-based fluoropolymer coating has been applied to the ALPOLIC 405/fr. Comparing with Kynar PVDF (polyvinylidene fluoride) both coatings are easy to process and durable, nevertheless, the Lumiflon coat is easier to repair with higher bendability, and it has a wider gloss and colour range than PVDF. Normally, the guarantee is given to the normal worst conditions that the product is expected to undergo in service. However, many products will achieve working lives longer than expected as the majority of the products will be at or below these conditions.

Project Name	**THK Building**	**Eisai Tsukuba Knowledge Center**	**AIG Nagasaki**	**Gakken Building**
Project Type	Office Building	Factory & Lab	Office Building and Civic Hall	Office Building
				
Location	Minato-ku,Tokyo, Japan	Tsukuba-City, Ibaraki, Japan	Nagasaki City, Japan	Shinagawa-ku, Tokyo, Japan
Project by	Obayashi Corporation	Kajima Corporation	Taisei Corporation	Shimizu Corporation
Client	Tatsuno Corporation	Eisai Co., Ltd.	AIG Group	Gakken Co., Ltd.
Completion	2017	2008	2005	2008
Product used	Architectural exterior panel 405fr Photocatalyst coat[92]	Architectural exterior panel (405 / fr)		
Construction Area	2000 m^2	1,200 m^2	5,500 m^2	3,100 m^2
Typical details	B-type		Edge Frame	



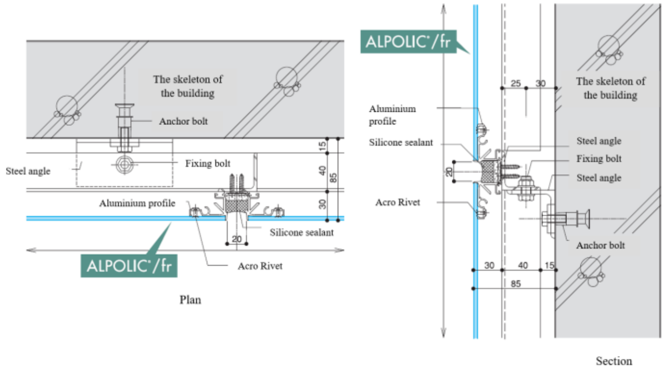


Table 7-2: Examples of various construction projects used ALPOLIC 405/fr as an exterior panel in Tokyo-Japan with typical reference details

[92] The Photocatalyst coat is a coating that applies a self-cleaning effect due to its oxidative decomposition power and hydrophilicity. By applying this coat to the outermost layer of the exterior panel, the dirt will be washing away by itself with rainwater and sunlight. Thus, it helps in reducing the cleaning maintenance costs and also realizing atmospheric pollution abatement at the same time.

Furthermore, this material has a 30% recycled content (14% pre-consumer recycled content and 16% post-consumer recycled content). The resource and material efficiency index has been shown in **Figure 7-3.**

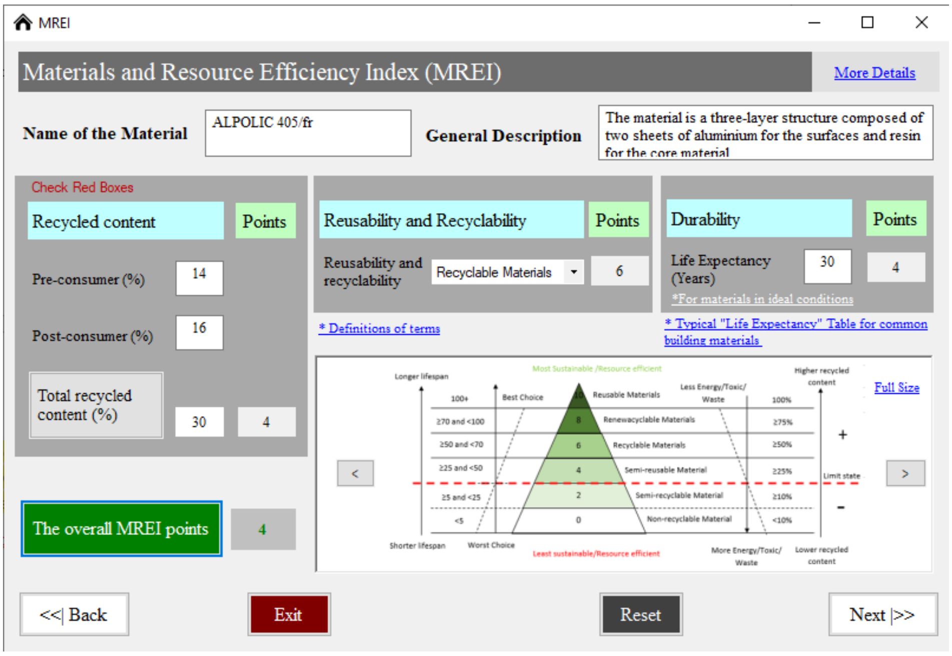


Figure 7-3: Materials and Resource Efficiency Index of ALPOLIC 405/fr

7.1.1.2 Socio-Economic Performance Index

ALPOLIC 405/ fr is considering appropriate material's options for the modern architectural design of ventilated rain-screen cladding façade system and decorate façade for both external and internal applications. In Japan, the raw materials are imported and manufactured locally and there are available labours to fix them into buildings. The initial cost (including material and construction costs) and replacement cost vary in the range of 350-400$ per meter square. Nevertheless, the high durability and maintainability of ALPOLIC could be beneficial in reducing the total life cycle cost. In general, the material performance is expected to decline after 20 years. However, regular washing with water (about 1 year) or neutral washing agents is recommended to prevent the build-up of corrosive deposits especially in metal corroded environments such as coastal areas.

The service life of ALPOLIC subjected to standard service conditions is predicted (30 years). Also, the building design life (50 years), and the average interest rate (2.44%) have been considered for the life cycle cost calculation. The socio-economic performance index cannot be determined without comparing the life cycle cost of ALPOLIC material with other available alternatives. Therefore, the life cycle cost is assumed to be below or equal to the average life cycle cost of other competitors (for example solid aluminium panels). **Figure 7-4** shows the achieved points and the socio-economic performance of ALPOLIC 405/fr.

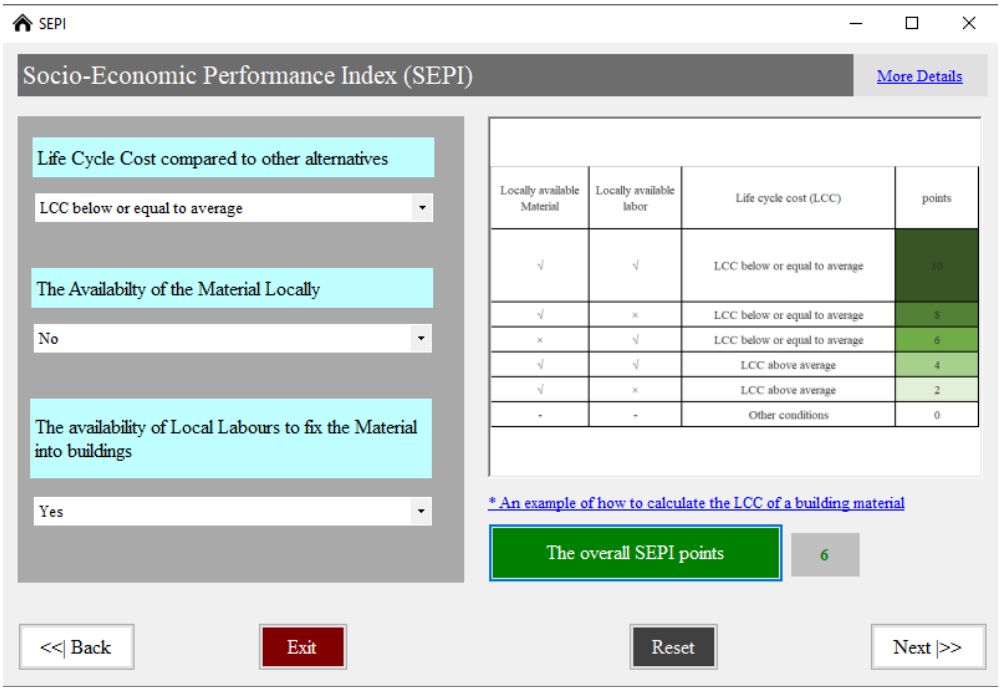


Figure 7-4: The Socio-economic index of ALPOLIC 405/fr

7.1.1.3 Health and Well-being Index

Selecting materials that maintain and promote good health and wellbeing should be considered from the very beginning in every project. The health and wellbeing index of ALPOLIC 405/fr has been examined by considering five criteria including hazardous chemical substances, moisture performance, fire-resistant performance, embodied carbon, and visual and thermal comfort.

Concerning hazardous components, some chromate treatments Cr(VI) may be used for coating metal and improving metal corrosion durability on the metal-resin adhesive layer. However, these compounds are toxic and increase the risk of lung, nasal, sinus cancer and other diseases. Therefore, trivalent chromium Cr(III), Zirconium, and titanium-based surface treatment agents have been used as alternatives to Hexavalent chromium.

Additionally, aluminium hydroxide, which is a hydroxide-based material, is used for the fire-retardant treatment of the core resin instead of halogen-based materials that may generate highly harmful substances during combustion. Similarly, for the added inorganic filler, there is a risk of inhaling dust generated during the cutting process to finish the composite board into the exterior panel, so substances with a high carcinogenic risk during suction are not used (for example, asbestos).

On the other hand, ALPOLIC 405/fr is considered one of the most common alternatives for exterior fire-resistant cladding, passed the fire requirements for exterior and interior panels in various countries. For instance, in the USA the material passed the ASTM E119 fire tests and in Canada, the ALPOLIC passed the CAN/ULC-S 134-92 Full-scale Exterior Wall Fire Test. In Japan, ALPOLIC 405/fr passed the heat release test for Non-combustible Material (ISO 5660-1) - certificate no. NM-1933. The aluminium sheets prevent the spreading of fire flames and the ignition is improbable.

Moreover, the material is non-permeable and does not absorb moisture at all. Regarding carbon footprint, the estimated embodied carbon coefficient of ALPOLIC 405/ fr is 19 $KgCo_2/Kg$ which is high compared to the majority of construction materials. This high figure is commonly associated with aluminium mining and manufacturing (coil coating and laminating process) which entail an energy-intensive production process that makes it responsible for 1% of global greenhouse gas emissions and 2.5% of CO_2 emissions (Brough & Jouhara, 2020). According to Guo, Zhu, Yang, and Cheng (2019), the CO_2 emissions during the aluminium smelting process accounts for more than 68% of the overall emissions. Moreover, the carbon intensity of aluminium can vary significantly from virgin to recycled aluminium. For instance, increasing the recycled content percentage can reduce the embodied carbon by around 42% for aluminium with 50% recycled content (Cheung & Farnetani, 2015). Also, the selected ALPOLIC 405/fr (Solid colour, M9010 White-G30) has a solar reflectance index of 82 which can decrease indirect solar gain in buildings and reduce the urban heat island effect. See **Figure 7-5**

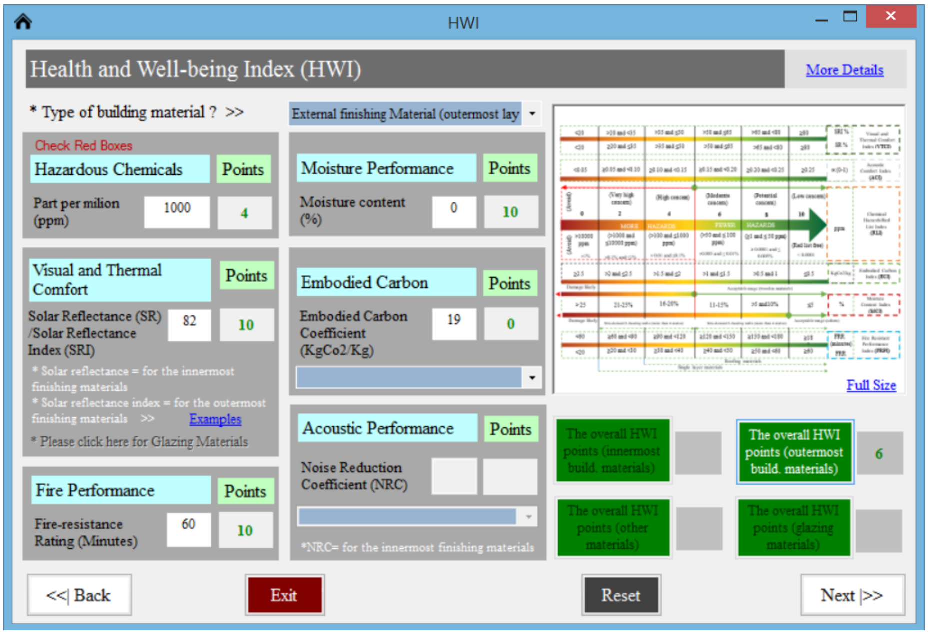


Figure 7-5: Health and well-being index of ALPOLIC 405/fr

7.1.1.4 Energy Efficiency Index

It is widely known that virgin aluminium metal requires a huge amount of energy to produce. Generally, around 50% of the required primary energy is consumed in the smelting process (Stacey, 2015). The embodied energy of aluminium is 155 MJ/Kg for typical aluminium and approximately 28.8 MJ/Kg for secondary aluminium (University of Bath, 2011). However, around 70 % of virgin aluminium is recovered and reused. The energy required for recycled aluminium is only about 5% of the energy required for virgin aluminium (Jeswiet, 2017).

The embodied energy of a 4mm thick Aluminum composite panel can reach up to 1196 MJ/m² (R. Crawford, Stephan, & Prideaux, 2019) in which aluminium coil could represent approximately 40% of the total sum. Therefore, increasing the percentages of recycled aluminium in the production of ALPOLIC material could achieve dual benefits; minimizing the use of natural resources and reducing embodied energy and CO_2 emissions.

Moreover, ALPOLIC 405/fr has a lower thermal conductivity than solid metals like aluminium (210 W/m·K) and steel (45 W/m.K) and can provide excellent exterior stability within a range of temperature from -50 to +80. However, the combination of ALPOLIC 405/fr and other envelope layers have the largest impact in determining the overall energy efficiency (heat transmission coefficient) of the envelope and building. **Figure 7-6** shows the energy efficiency index of ALPOLIC material.

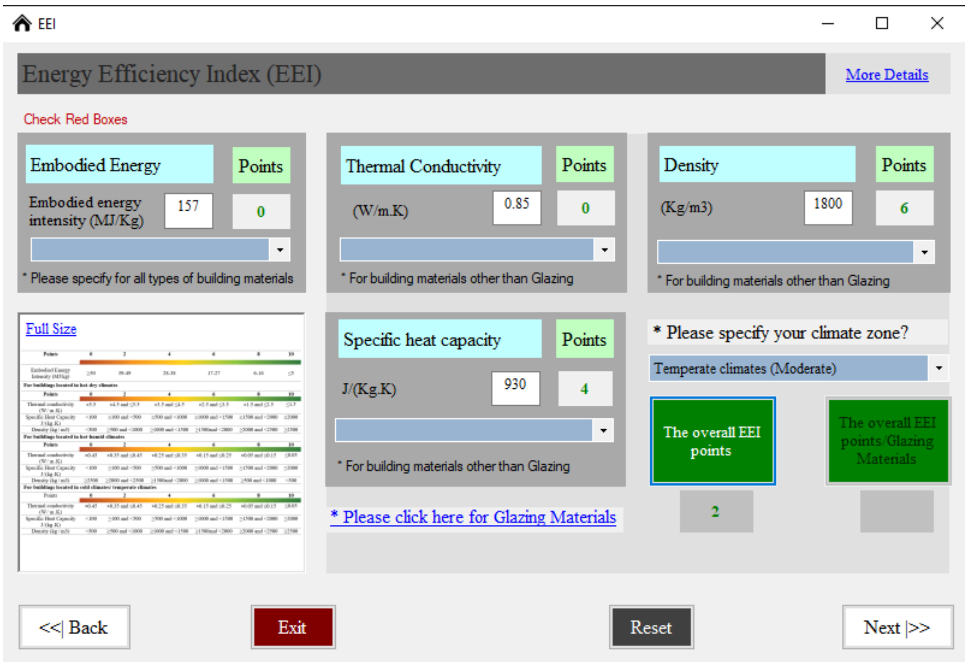


Figure 7-6: Energy efficiency index of ALPOLIC 405/fr

7.1.1.5 Water Efficiency Index

Construction materials manufacturers use water in a wide variety of ways throughout their manufacturing processes. Therefore, further analysis and development of tools are needed to fully assess the water footprint of these products. Few databases are currently available or accessible in the construction sector to facilitate adequate accounting for water use and consumption. Although the estimation of embodied water of building materials is conceptually complex, it is highly required to fully quantifying and assessing the overall environmental impacts of construction products and to manage water more effectively.

There is no available data concerning the embodied water of ALPOLIC 405 fr. The product is composed of two sheets of aluminium and core material. Aluminium consumes significant water resources to produce and have a large water footprint. Water forms an essential raw material to produce alumina (bauxite ore refining into alumina), dust mitigation, road watering and vehicle and equipment cleaning during mining operations, and the ingot-casting process during smelting. Reports on U.S. plants (Conklin, 1956) determined that the average water requirements of alumina plants are 0.66 gallons (2.5 litres) per pound. In the worldwide assessment, an average of 14.62 gallons (55.3 litres) per pound is assumed for the aggregated aluminium production (Buxmann, Koehler, & Thylmann, 2016).

Additionally, a considerable amount of water is consumed in the Aluminium coil coating line for cleaning and pre-treatment, and for cooling tower recirculation used. According to the Environmental Performance in Construction (EPiC) Database (2019), the embodied water of a typical 4mm thick Aluminium composite panel can reach up to 1174 Liter per square meter. It should be noted that the water used for the coil cleaning process can be reused several times before being disposed of properly which help in cutting the freshwater consumption level. Nevertheless, adopting new solutions and increasing the use of recycled water within the production plants for specific processes is consider powerful strategies to reduce freshwater use.

7.1.1.6 The Final Sustainability Index

The overall sustainability index of ALPOLIC 405/fr is 0.388 which indicates that the material has the capability to achieve almost 39% of the targeted sustainable development goals (see **Figure 7-7**). The results showed that the material achieved higher points in the socio-economic performance index and health and well-being performance index.

Nonetheless, lower indexes (highlighted in red) have been observed on both the energy efficiency index and water efficiency index.

In respect to the resource efficiency index which considered a central indicator for measuring the material flows and ensuring sustainable resource and durable products, four points are achieved. This figure is sufficiently high if it is taken into account that the resource efficiency index has the largest share in the overall sustainability index.

Figure 7-7: The final sustainability index of ALPOLIC 405/fr

7.1.2 Case study II

In this section, two types of external finishing materials are assessed to be used in a two-story detached house in Tokyo prefecture-Japan. These materials are Fiber cement siding and Metal siding. The reasons for choosing this housing typology and materials as a case study are i) the detached houses are the most common type of family home and the need to expand their sustainability by promoting effective methods are broadly considered in the society; ii) the selected materials are currently used abundantly in residential buildings in Japan and there is a need to check their impacts in creating sustainable buildings.

The case study is mainly examined to simplify the complex material selection concept, generate hypotheses, improve analytical thinking, validate the proposed tool and method in real-world applications, and also give more insights regarding the research topic.

Moreover, the data concerning the value of each material's sub-criteria (alternative properties) were obtained via interviews and questionnaires distributed to the local building materials manufacturers. The efficiency of each alternative is measured for each decision criterion. Subsequently, materials ranked using an application tool developed by the authors and the results are compared. In this process, the decision-maker attempts to select the best alternative material with a higher sustainability index (the material that scores higher points in most criteria).

7.1.2.1 Overview of siding materials

I. Fiber Cement Siding

This is the most commonly used exterior siding material in housing projects in Japan (more than 70% of new houses are made of this ceramics siding). The material was introduced to the construction industry in the 1980s as an alternative to asbestos cement siding products. It has been manufactured compliant with Japanese industry-standard (JIS A 5422). Fibre cement panels manufactured from a pressed, stamped, and autoclaved mix of cement, fly ash (a byproduct of coal-burning), silica, recycled materials, and wood fibres (See **Figure 7-8**). Commonly, cement is reinforced and hardened by using wood fibres or wood chips.

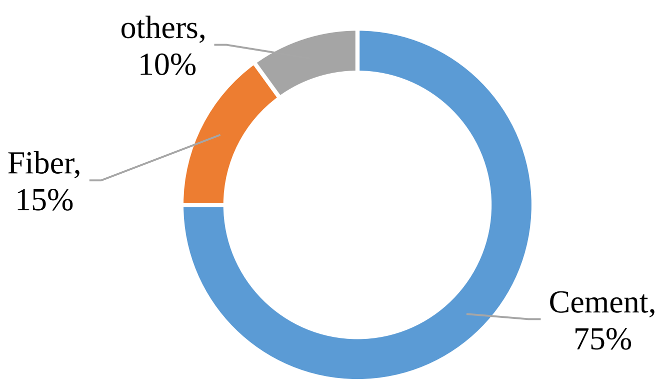


Figure 7-8: The components of fibre cement siding

Sheet sizes vary slightly in a range between 455 × 3,030mm and 455 × 1,820mm. Also, the most common sheet thicknesses are 14, 16, 18, and 21mm. Fibre cement panels are lightweight compared to other siding panels. Several textures and colour patterns are available in the market to satisfy the designers and clients need. The pre-finished panels are cut and fix on the site using a clip or nail installation (dry-wall construction method).

II. Metal Siding

Metal siding is a common exterior wall panel for houses in Japan with a broad array of colours and textures which can imitate natural materials such as stone, wood, and plaster walls. The sheet is lightweight and has an excellent heat insulation capacity. Atypical metal siding is composed of a high-performance metal outer wall material (surface material; 55% molten aluminium-galvanised steel sheet) with a heat-insulating material (core material) and aluminium laminated paper (back material). The surface material is generally coated with a highly corrosion-resistant GL-plated steel sheet. Adhesives are used to glue the aluminium sheets to the core. Typical sheet size varies between 18×385×3000mm and 18×385×4000mm. **Table 7-3** shows the general specifications of the selected materials.

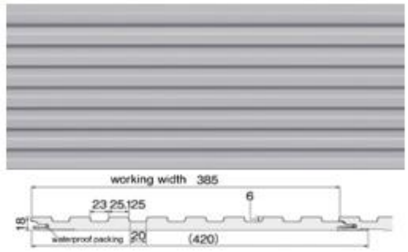
Products Information	**Fibre Cement Siding**	**Metal Siding**
		
Dimension	455x 3,030mm	385×3000mm
Thickness	16mm	18mm
Normal Weight	26 kg / sheet	5.7kg / sheet
Installation	Clip System	Clip System
Texture and colour	Natural Stone Texture/cream colour	Light Metallic Silver/ Metallic
Coverage	1.38m²/piece	1.16m²/sheet
Initial material cost	4,570 Yen/m^2	5,940 Yen/m^2
Sub-structure	Timber framing, Steel framing	Timber framing, Steel framing

Table 7-3: General products specifications

7.1.2.2 Comparison and analysis of the results

Resource and material efficiency index (RMEI)

Fibre cement siding scored higher points than Metal siding in the recycled content index; the former is manufactured by using approximately 27-37% pre-consumer products and between 1-2% post-consumer products from the overall material weight. Generally, fly ash is used as pre-consumer material and the fibre cement scraps obtained from construction sites are used again as post-consumer material in the production of new sidings. It should be pointed out that, the wood fibre or wood chip is used as virgin materials so it has been excluded from the total recycled content percentage. Conversely, Metal siding is manufactured by utilizing virgin materials (metal and polyurethane or polyisocyanurate foam). Furthermore, Fiber cement siding and Metal siding are technically semi-recyclable and recyclable respectively, nevertheless, there is currently no program for incorporating recycled materials back into production, so most of the materials end up in the landfill.

In terms of durability, both materials have a longer life expectancy and several manufacturers offer different warranties against fading and discolouration. The warranties range from 10 to 15 years. Lastly, both materials scored the same points under the material and resource efficiency index (See **Table 7-4**).

Building materials alternatives		Recycled content –RC (%)			P.	Reusability and recyclability	P.	Durability (life expectancy in years)	P.	**The overall achieved points**
		Pre-consumer	Post-consumer	Total RC (%)						
I	Fibre cement siding	27-37	1-2	28-39	4	Semi-recyclable	2	20-50	6	**4**
II	Metal siding	0	0	0	0	Recyclable	6	20-50	6	**4**

Table 7-4: Resource and material efficiency index for the selected materials

Socio-economic performance index (SEPI)

The raw materials for both products are imported from outside the country and manufactured locally, nonetheless, there are available labours to fix them into buildings. The materials costs vary between 4,570 Yen/m^2 for Fiber cement siding and 5,940 Yen/m^2 for Metal siding. However, the true costs of the two materials can't be measured without examining maintenance, replacement, and demolition costs over the building lifetime.

Generally, Metal siding requires maintenance every 20-30 years, while Fiber cement panel needs maintenance approximately every 10-30 years. Furthermore, the average interest rate of Japan (2.44% from 1972 until 2020) has been considered to calculate the life cycle cost of the materials.

Additionally, the expected lifetime of the detached house has been assumed as 40 years (the average lifespan of detached houses in Japan) (KOMATSU & ENDO, 2000). Also, a reference cost value has been counted for construction, maintenance and demolition for both materials.

Although the socio-economic performance index of Metal siding is higher than Fiber cement siding, the estimation of the life cycle costs of the two materials is too close (See **Table 7-5**).

Building materials alternatives		Initial costs (Yen/m^2)	Maintenance costs (Yen/m^2)	Demolition costs (Yen/m^2)	(LCC) (Yen/m^2)	Raw Materials are produced locally	Locally available labours	**The overall achieved points**
I	Fibre cement siding	11,700	3,824	4,000	38,574.62	No	Yes	**0**
II	Metal siding	10,000	4,667	4,000	27,478.09	No	Yes	**6**

Table 7-5: Socio-economic performance index for the selected materials

<u>Health and well-being index (HWI)</u>

The overall achieved points indicate that both materials have the same impact on the health and well-being index. Fibre cement siding does not contain any asbestos, but it may contain low concentrations (<1 part per million (ppm)) of Polystyrene and Chromium (which can cause adverse health effects). Also, cutting the fibre cement siding during the installation process might release silica dust into the air. Silica dust is extremely hazardous to health and could cause respiratory problems and other diseases. Thus, taking proper safety measures on the construction sites and attaching a standard shop vacuum to a dust-collecting circular saw have been found as a practical solution to mitigate this problem.

On the other hand, although it is widely known that polyurethane insulation foam or polyisocyanurate foam (core material in the metal siding) contain halogenated flame retardants which might cause dense and toxic smokes during burning, the data showed that the selected Metal siding doesn’t include any of these or other examined hazardous substances.

Furthermore, Fiber cement siding contains higher moisture content than metal siding when manufactured which makes the latter more efficient in mitigating moisture problems that might happen over time. In terms of fire resistance performance, both materials are non-combustible and they have a high fire-resistance rating (45 minutes). In terms of embodied carbon, Metal siding requires a comparatively large amount of energy to manufacture than Fiber cement siding resulting in a high-embodied carbon footprint. **Table 7-6** demonstrates the health and well-being index of the selected options.

Building materials		H.C.C (ppm)	P.	M.C. (%)	P.	F.R.R. (minutes)	P.	E.C.C ($kgCo_2/kg$)	P.	S.R.I (%)	P.	**Achieved points**
I	Fibre cement siding	>1	10	≤20%	4	45	6	1.28	6	89	10	**6**
II	Metal siding	0	10	≤5%	10	45	6	14.28	0	65	6	**6**

Table 7-6: Health and well-being index for the selected materials

Note: H.C.C= Hazardous Chemical Content, P. = Points, M.C= Moisture Content
F.R.R. = Fire Resistance Rating, E.C.C= Embodied Carbon Coefficient, S.R.I= Solar Reflectance Index.
* The corresponding embodied carbon coefficient is following a cradle-to-gate approach.

Water efficiency index (WEI)

The embodied water intensity value of Metal siding is not available which gave preference to the Fiber cement siding for scoring high points in this index. In most cases, the processing and manufacturing of Metal siding are typically more water-intensive than other façade materials. Conversely, the data shows that little water is used in the production of fibre cement siding (See **Table 7-7**).

Building materials alternatives		Embodied water intensity (KL/Unit)	**The overall achieved points**
I	Fibre cement siding	0.66 KL/m^2	**10**
II	Metal siding	NA	0

Table 7-7: Water efficiency index for the selected materials

Note: NA: Data not available. * The corresponding embodied water is following a cradle-to-gate approach. KL/m^2: kiloliters per square meter.

Energy efficiency index (EEI)

Fibre cement siding has a better energy efficiency index than Metal siding because less energy is consumed during the manufacturing process in the former. Although the insulated Metal siding is assumed to expend a large amount of embodied energy, it offers continuous insulation values (high R-values) and built-in thermal breaks, hence it is expected to be effective in reducing operational energy costs of heating and cooling (See **Table 7-8**).

Building materials alternatives	Embodied energy intensity (MJ/kg)	Points	Thermal Resistance						**The overall achieved points**
			Thermal conductivity (W/m.k)	P	Specific heat capacity J/(kg.k)	P	Density (kg/m3)	P	
I Fibre cement siding	15.3	8	0.26	4	840	4	1380	4	**6**
II Metal siding	62	0	0.041	10	1470	6	196	0	**2**

Table 7-8: Energy efficiency index for the selected materials

* The corresponding embodied energy intensity are following a cradle-to-gate approach.

<u>The overall sustainability index (SI)</u>

The final sustainability index of Fiber cement siding (0.49) is higher than Metal siding (0.39) indicating that the former material could help in the achievement of approximately 49% of the sustainable development goals (SDGs) that building materials can realize. Fibre Cement siding has been selected as the best façade option for the detached house. Furthermore, some indexes have been highlighted in red to clarify the shortcomings in material values and properties included under the main criteria. The red highlights give a warning to the decision-maker to review the assessed materials before making their final decision (See **Figure 7-9**).

Figure 7-9: The final sustainability index of the selected materials

7.1.2.3 Discussion

The demonstrated case study showed that the selected Fiber cement siding scored a higher sustainability index (49%) than the Metal siding (39%), thus, it has been chosen as a façade material for the detached house. However, some points need to be addressed to obtain a better index.

It is important to note that increasing the use of fly ash, wood chips (pre-consumer and post-consumer) and recycled waste as a cement replacement besides enabling the reusability and recyclability approach must be considered as the main two strategies to achieve more points in the material resource efficiency of Fiber cement siding. Likewise, empowering the recyclability of metal siding and its core while encouraging the use of recycled products is fundamental to attain a higher resource efficiency index. Currently, several concerns regarding the complexity and expenses of recycling the insulation core of the metal siding and its economic and environmental impacts are still being sought.

Also, higher points in the socio-economic index could be obtained if the raw materials of both products are produced locally. Furthermore, big differences in life cycle costs could be spotted if the service life of the detached house is extended. For instance, in a detached house with 50 years life span the estimated materials life cycle cost might reach up to 55243.94 Yen/m^2 for Fiber cement siding and 30338.22 Yen/m^2 for Metal siding. Therefore, these figures indicate that Metal siding is preferable for use in buildings with longer life expectancy.

In the case of fibre cement siding, increasing the replacement percentage of cement by fly ash and wood fibres is considered a prominent solution to mitigate hazardous chemical substances such as chromium and silica dust. Similarly, promoting the application of polyurethane foams with halogen-free flame retardants could help in producing more sustainable insulated metal sidings.

Also, the results show that the embodied carbon coefficient and embodied energy intensity of metal siding are too high which hindering the material to achieve higher points in health and well-being index and energy efficiency index. These high figures are commonly associated with metal mining and manufacturing (ex. smelting and refining processes, coil coating and laminating process) which entail an energy-intensive production process. However, increasing the recycled content percentage while promoting the reusability and recyclability approach are considered practical strategies to reduce the embodied energy, carbon intensity and global greenhouse gas emissions associated with the production of metal siding. On the other hand, advancing the application of alternative cementitious materials that replace or supplement the use of cement in fibre cement siding can reduce fuel consumption and lower greenhouse gas emissions.

With regard to water efficiency, few databases are currently available or accessible in the construction sector to facilitate adequate accounting for water use and consumption. Therefore, further analysis and development of tools are needed to fully assess the water footprint of construction products. Nevertheless, adopting new solutions and increasing the use of recycled water within the production plants for specific processes is consider powerful strategies to reduce freshwater use.

7.1.2.4 Sensitivity analysis

A sensitivity analysis was performed to explore the effect of the systematic change of the input parameters in the output variable and to estimate the rationality of the developed model. This was conducted by changing the values of the material under some criteria with low indexes to see their effect on the overall sustainability index. The following measures are applied:

A. The percentage recycled content is assumed to be 50% for the two alternatives.

B. All materials are considered to be produced locally and there are local labours to fix them into the detached house.

C. Other criteria values are unaltered.

The results indicated that the model has considerable robustness to the change of weightings of criteria and the final index. Figure 7-10 shows the outcome of the discussed analysis.

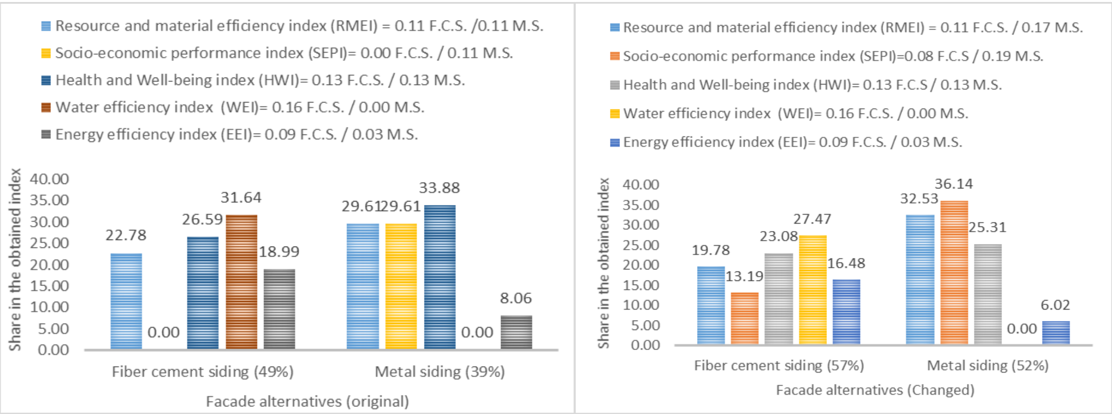


Figure 7-10: Results of sensitivity analysis.

Note: F.C.S. = Fiber cement siding; M.S. = Metal siding

7.1.3 Case study III

This case study demonstrates a practical analysis for selecting the most sustainable building façade alternative to be used in a detached house in central Tokyo-Japan. In contemporary Japanese architecture, two prototypes of houses are dominant; the single-family detached houses and the multiple-unit construction. The first archetypes are facing many challenges regarding extending their service life and the possibility of reusing and recycling their integrated components after demolition. The case study tests the applicability, compatibility, and clarity of the proposed decision-making approach for selecting building envelopes and assemblies from an early design stage. It is intended to show the possible extended use of the proposed framework.

The alternative façade assemblies (external walls) will be assessed by considering various criteria to show their role in the achievement of sustainable development goals. The criteria and their minimum acceptable range and weight have been discussed in chapter six. Nevertheless, questionnaires and interviews with local building material manufacturers, construction companies, and other peer-reviewed studies were adopted as the method of data collection.

7.1.3.1 Description of the building model

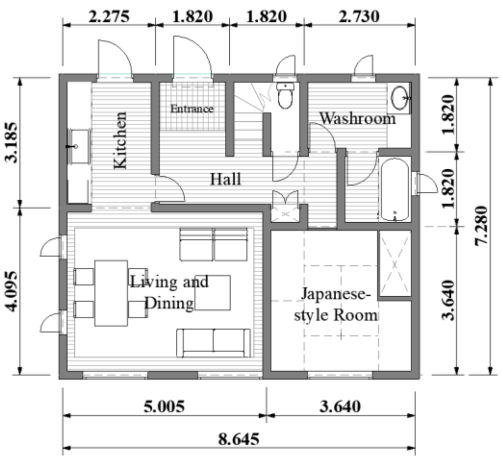
The reference house is a two-story detached house with a steel structure composed of metal stud framing, and metal stud components. The plan of the house[93] was designed taking into account the standard model of the Architectural Institute of Japan (AIJ) (IWAMURA, ISHIZAKI, YOSHIZAWA, & Nasu, 2005; Ohba & Lun, 2010). The total floor area of the house is 126 square meters and the ceiling height is 2.4 meters. To simplify the assessment, only the opaque envelope parts are different, while the rest of the house components including the structural frame as well as openings were considered unchanged. **Figure 7-11** shows the floor plans and an overview of the detached house.

7.1.3.2 Building envelope alternatives

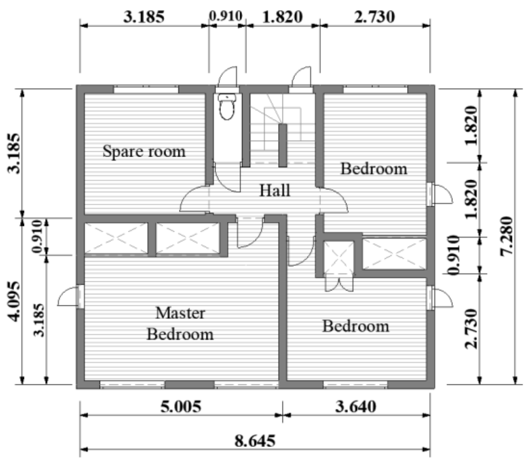
Two non-structural opaque facade systems (external walls) were identified as the most commonly used façade systems for detached houses in Tokyo; these systems are face-sealed and rainscreen facades systems. The Autoclaved Aerated concrete system (AAC or Hebel) has been selected as the first façade alternative. Generally, this system depends on the outermost layer of the façade (Hebel panel) to be sealed as the primary drainage

[93] The ground floor composed of living hall (~20.5 m^2), dining and kitchen (~13.00 m^2), Japanese style room (~1.25 m^2) besides the bathroom (~10.00 m^2). The first floor designed with master bedroom (~20.495 m^2), two children rooms (~20.00 m^2), spare room (~6.37 m^2), and toilet (1.65 m^2).

line. It is generally acknowledged that the system has a high thermal mass, thermal insulation, fire rating, and long life expectancy.

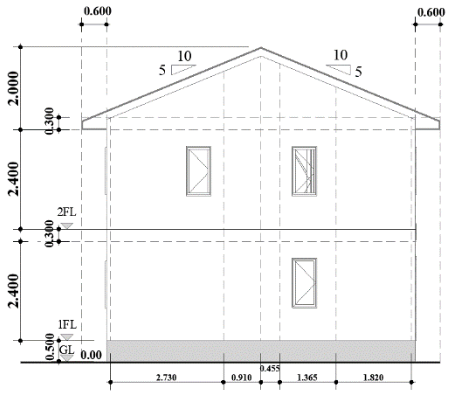


1st floor plan



2nd floor plan

Preliminary generic perspective



East elevation

Figure 7-11: Outline of the detached house model

On the other hand, the rainscreen fibre cement siding system has been selected as a second alternative. In this system, the fibre cement siding (outermost skin) designed to protect the inside of the building from external weather elements. This type of façade is growing in popularity for new and refurbished buildings in Japan. It has been designed to prevent moisture from entering inside the building by creating a ventilated cavity (air gap) between the outer facade skin and structural elements. Besides improving the indoor environment and mitigating moisture penetration, this ventilated facade has been used widely for aesthetic reasons, improve the energy performance of buildings, provide good sound and fire insulation (Marinosci, Strachan, Semprini, & Morini, 2011). The composition of the two systems is explained in **Table 7-9**.

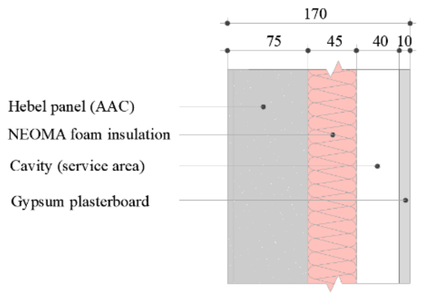
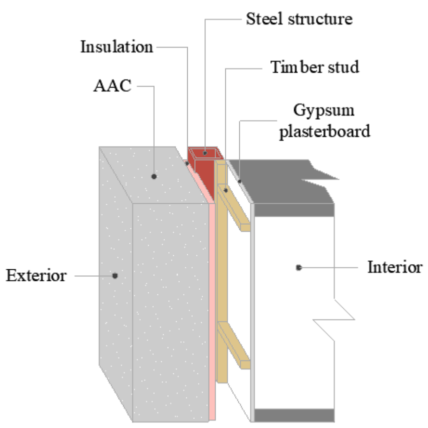
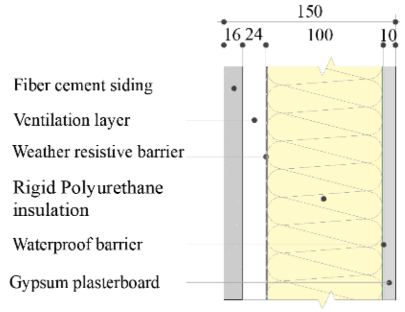
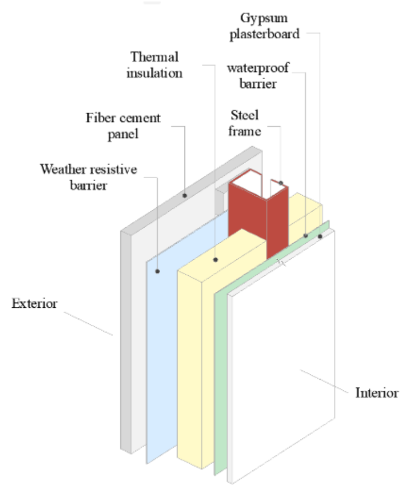
Façade system	Hebel Construction face-sealed system	Rainscreen fibre cement siding system (ventilated system)
Typical cross-section		
Layers (from the outermost layer to the innermost layer)	Layer 1 (Autoclaved Aerated Concrete (Hebel panel))	Layer 1 (Fibre cement siding)
	Layer 2 (NEOMA foam insulation)	Layer 2 (Ventilation Cavity)
	Layer 3 (Cavity (service area))	Layer 3 (Weather resistive barrier)
	Layer 4 (Gypsum plasterboard)	Layer 4 (Rigid urethane insulation)
		Layer 5 (Waterproof barrier)
		Layer 6 (Gypsum plasterboard)

Table 7-9: The selected façade systems and their components from the outermost layer to the innermost layer.

<u>Building materials integrated into Hebel construction face-sealed system</u>

I. Hebel panel

Hebel is a representative example of Autoclaved Aerated Concrete (AAC). Also known as autoclaved lightweight concrete (ALC), Hebel block, cellular concrete, and porous concrete. The main raw materials of Hebel are silica rock, cement, and quick lime, mixed with water and aluminium powder, and foamed. After partial hardening, the material is cut into panels, and cured in an autoclave at a temperature of approximately 180°C and a pressure of 10 atms (standard atmosphere) for a sufficiently long duration. This hydrothermal process produces lightweight panels (up to 80% of its volume made up of air) with stable tobermorite crystals ($5CaO \cdot 6SiO_2 \cdot 5H_2O$) and high thermal insulation properties. The reinforcing steel in AAC is coated with rust-resistant materials before casting. Hebel panel has high fire resistance properties and superior thermal properties[94]; it has a thermal conductivity of 0.15 W/m.K (dry air). Also, the panel has a specific gravity of 0.6 and is approximately 1/4th of the weight of standard concrete, thus, it can achieve the complete prerequisites for the external envelope of a building as a single component. The material is recyclable and the cut-offs from building sites can be reused as raw materials for cement, and Hebel itself. It can be used in a broad variety of structural and non-structural applications (cladding application). In Japan, around 2.5 million cubic meters of ACC is produced yearly.

II. NEOMA foam insulation

NEOMA foam is a phenolic-foam insulation panel (less than 100 microns) produced with a hydrocarbon foaming agent (HC), rather than ozone-depleting agents such as Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), or Hydrofluorocarbons (HFCs). The manufacturing starts by synthesizing the phenolic resin from the raw materials. The wet resin is added to a bottom layer of facing, the foam is heated while expanded to meet the top layer. As it dries the rigid insulation core is bonded to the layers. Afterwards, the panels moved on to a secondary oven to cure and harden under pressure and heat, becoming bright pink in colour. The panels are then cut into the desired sizes. The material is considered a high-performance insulation product (0.020 W/m.K) that is light, fire-resistant, durable, and ecological. Also, the material is recyclable which was long regarded as infeasible for phenol foam.

III. Gypsum plasterboard

Gypsum plasterboard is a standard board consisting of gypsum and paper and it is widely used for most applications such as interior walls, ceilings, and partitions. The product is suitable for use as base layers for decorations with paint wallpaper. The gypsum raw materials involve raw gypsum, domestic by-product gypsum, and waste gypsum boards. The manufacturing process is typically started by the calcination process wherein the gypsum raw materials are baked in a furnace and made into calcined gypsum which will

[94] The panel was originally utilized in cold climates as it provides good thermal resistance and keeps the indoor zones warm. Thenceforward, it has been used widely worldwide in the areas where air conditioning is required.

solidify when it reacts with water. Afterwards, the calcined gypsum is mixed with water to make a slurry (muddy state). Then, the slurry is poured and sandwiched between two sheets of thick paper (board liners). As a final process, the boards are sent to a drying machine to remove excess water content. Gypsum Boards are recyclable; the waste gypsum boards are collected and recycled in the production plants.

Building materials integrated into the rain-screen fibre cement siding system

I. Fibre cement siding/panel

Fibre-reinforced cement siding is mainly exterior composite material produced by a pressed, stamped, and autoclaved mix of cement, fly ash, silica, recycled materials, and wood fibres (chips). The material moulded and pre-finished applying a durable multi-layered paint method to replicate varied textured finishes. Generally, wood-based material and cement are mixed with a small amount of water and press-moulding. Because it is manufactured using domestic wood chips, the panel is considered as carbon storage until it is discarded. The panel is 16×455×1,820mm and has a thermal conductivity of 0.26 W/m･K, and a density of 1380 kg/m^3.

II. Weather-resistant barrier

The Weather-resistive barriers (building wrap or house-wrap) are primarily designed to protect the wall assembly against exterior water penetration (rain). It allows the penetrated water beyond the fibre cement siding to drain away from the wall assembly by providing a secondary moisture drainage plane. Generally, the weather-resistive barrier is combined with flashing and other supporting materials. However, a weather-resistive barrier expands the building durability, reducing maintenance costs, and diminishing the moisture-related risks. Furthermore, it functions as an air barrier to reduce air infiltration and reduce energy use. The barrier is a polyethylene-based sheet that permeates moisture that enters through the wall while stopping wind and water. Non-woven fabric is used as a base material to increase the thickness by 0.1mm to ease the installation.

III. Pre-formed Rigid urethane foam

Urethane insulation foam is a polymer (plastic) produced by mixing and reacting two main raw materials. Generally, the material produced by reacting polyisocyanurate and isocyanate-reactive compounds in the presence of a blowing agent. The blowing agents are responsible to expand the foam to its rigid form and create fine cellular structures throughout the polymer processing (Fangareggi & Bertucelli, 2012). The

Hydrofluoroolefins (HFOs) have been used as blowing agents (a 4th generation blowing agent) with zero ozone depletion potential and low global warming potential (≤ 1). The rigid urethane foam insulation has an expected thermal conductivity value of 0.026 W/m·K and a density of 35 kg/m^3. In general, the material can be used in a temperature range from -70 °C to +100 °C.

IV. Waterproof barrier

The function of a waterproof barrier (waterproof sheet) is to retard the migration of water vapour. It works as a vapour barrier (vapour retarders) to retard the migration of moisture by vapour diffusion into the building facade. Hence eliminating the internal condensation and maintaining the performance of the rigid urethane foam insulation of the façade (create an air/vapour tight layer on the inner side of the insulation layer). A Non-woven polyethylene (PE) plastic sheet is used as a vapour barrier. It is fabricated by polymerising ethylene monomers using a catalyst (typically metal chlorides or metal oxides). The material has low strength and rigidity but high impact strength, ductility and waterproof.

7.1.3.3 Results and Discussion: Application of the proposed sustainability assessment approach to the case study

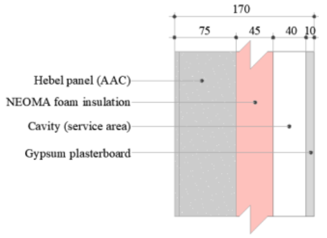
Resource and material efficiency index (RMEI)

The two systems were investigated in terms of recycled content, reusability and recyclability potential, design for deconstruction/disassembly applicability, and life expectancy to show their overall resource and material efficiency index. Regarding the percentage of recycled content, Alternative B revealed a higher recycled content than Alternative A; this is mainly due to the great weight of fibre cement siding to total (62.27%) with higher recycled content (39%).

In fibre cement panels, fly ash and wood chips are utilized as pre-consumer products while fibre cement scraps as post-consumer material. Likewise, the Hebel panel represented 83% of alternative A weight, but their total recycled content is very low (2.5%) and that affect the assembly total recycled content. Additionally, higher recycled content spotted on the gypsum plasterboard (27.5%), in which byproduct gypsum from thermal power plants and fertilizer mills (pre-consumer) and gypsum waste boards from construction sites (post-consumer) are used for the core and the recycled paper for the paper facing. **Table 7-10** shows the recycled content of one square meter of the selected façade alternatives.

Building Assembly (A)

Outside

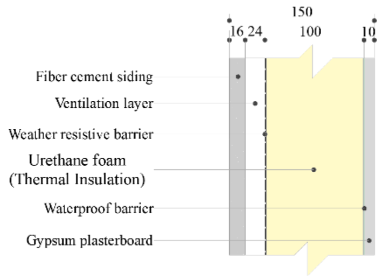


Inside

Assembly layers (from the outermost layer)	Weight (%) to Total	Post-consumer recycled content (%)	Pre-consumer recycled content (%)	Proportional post-consumer recycled content (%)	Proportional pre-consumer recycled content (%)
Layer 1	83	0	2.5	0	2.08
Layer 2	2.25	0	<5	0	0.11
Layer 3	NA	NA	NA	NA	NA
Layer 4	17.75	7.5	20	1.33	3.55
Total weight	**100**				
Assembly post-consumer recycled content (%)				1.33	
Assembly pre-consumer recycled content (%)					5.74
Assembly total recycled content (%)					**7.07**

Building Assembly (B)

Outside



Inside

Assembly layers (from the outermost layer)	Weight (%) to Total	Post-consumer recycled content (%)	Pre-consumer recycled content (%)	Proportional post-consumer recycled content (%)	Proportional pre-consumer recycled content (%)
Layer 1	62.27	2	37	1.25	23.04
Layer 2	NA	NA	NA	NA	NA
Layer 3	2.65	0	0	0	0
Layer 4	9.87	≤10	≤10	0.99	0.99
Layer 5	2.65	0	0	0	0
Layer 6	22.56	7.5	20	1.69	4.51
Total weight	**100**				
Assembly post-consumer recycled content (%)				3.93	
Assembly pre-consumer recycled content (%)					28.54
Assembly total recycled content (%)					**32.47**

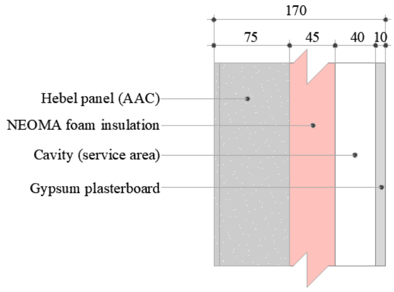
Table 7-10: The recycled content of the selected façade alternatives in square meter

Note: NA= Not Applicable.

On the other hand, both alternatives score 2 points in the reusability and recyclability criteria (see **Table 7-11**). It should be noted that the end-of-life option for the materials has been determined based on their future potentiality to be reused or recycled and not on their current status. The majority of the integrated materials have the potential to be semi-recyclable. In view of this, the Hebel panel wastes can be used as raw materials for the production of new Autoclaved lightweight concrete panels or can be integrated into cement production; polyurethane foam wastes can be used as particleboard, for energy (heat) recovery, or chemical recycle into methanol (C1) or acetic acid (C2); NEOMA foam insulation waste can be used for energy recovery.

Building Assembly (A)

Outside

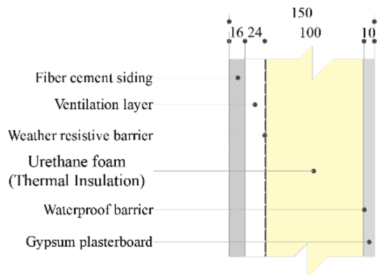


Inside

Envelope layers	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	
Material name	Hebel panel	NEOAM insulation	Cavity (service area)	Gypsum plasterboard	**Average achieved points**
Material's type	Semi-recyclable	Semi-recyclable	NA	Recyclable	
Points	2	2	NA	6	**2**

Building Assembly (B)

Outside



Inside

Envelope layers	**Layer 1**	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**	
Material name	Fibre cement siding	Vent. layer	Water resistive barrier	Urethane foam insulation	Waterproof barrier	Gypsum plasterboard	**Average achieved points**
Material's type	Semi-recyclable	NA	Non-recyclable	Semi-recyclable	Non-recyclable	Recyclable	
Points	2	NA	0	2	0	6	**2**

Table 7-11: The total achieved points of the selected alternatives in terms of reusability and recyclability

Note: NA= Not Applicable.

Furthermore, although dry connections are mostly used in both alternatives, the application of the design for disassembly is not considered in them. Thus, they will be demolished at the end of the building lifetime.However, some of the façade's layers will be semi-recycled or recycled and the rest will be sent as wastes to landfills. As regards the lifetime expectancy, Alternative A is expected to last longer than Alternative B. The Hebel system is expected to have 60 years of durability, while the fibre cement rain-screen siding system is likely to have 30 years. In the end, both alternatives have the same score (2 points) in this index. See **Figure 7- 12**

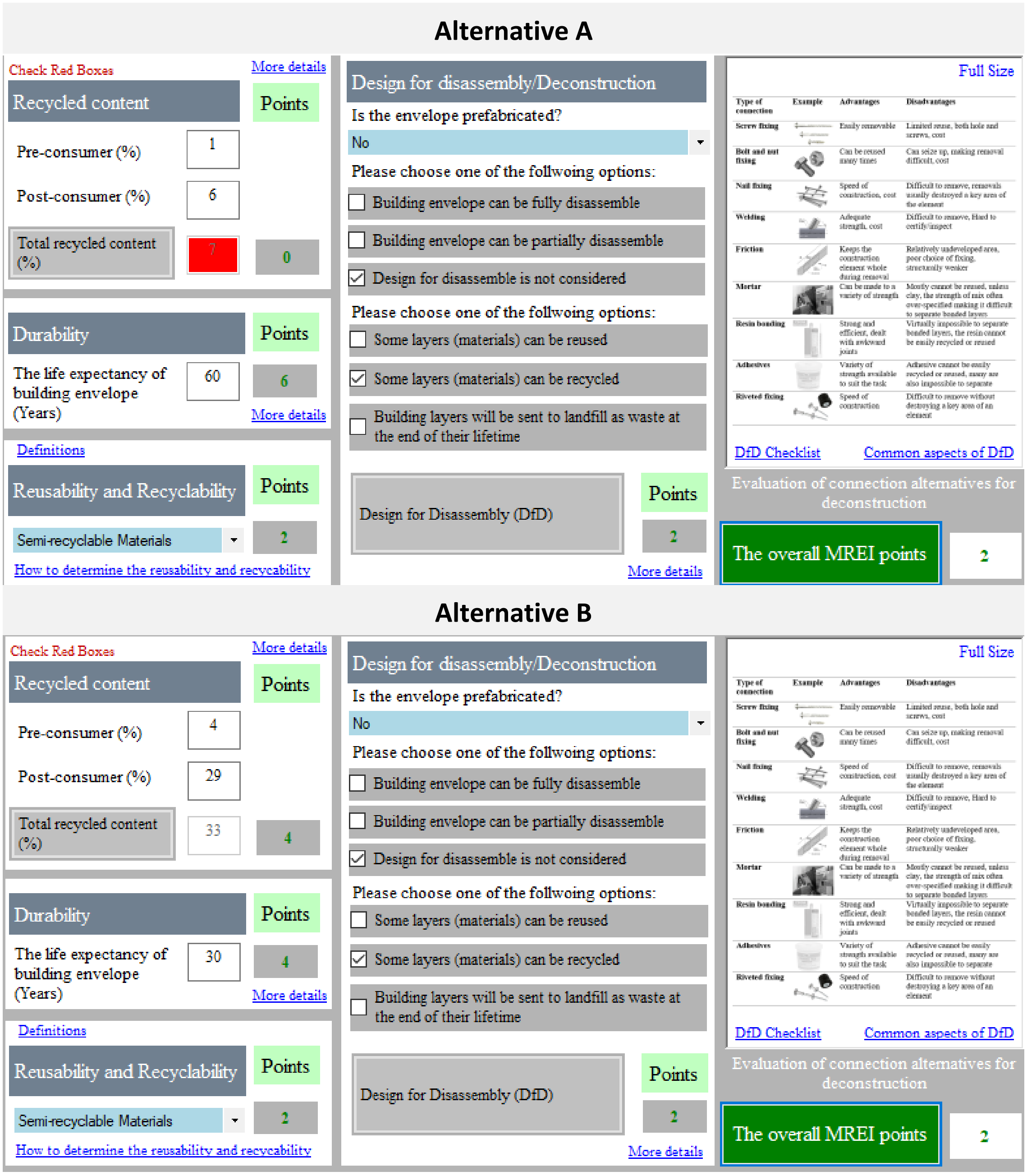


Figure 7-12: The resource and material efficiency index of both façade assemblies

Socio-economic performance index (SEPI)

This index intended to assess social and economic sustainability impacts of façade alternatives by considering their associated life cycle costs, checking the availability of their integrated components in the local construction market and ensuring that there is available labour to fix them into buildings. However, estimating a detailed life cycle cost of each alternative can be challenging and require the use of affordable, reliable and well-documented statistics.

The initial construction cost of alternative A and alternative B (for the complete façade system including the structural frame) was estimated as 312,000 Yen/m^2 and 200,000 Yen /m^2, accordingly. The maintenance cost of alternative A and alternative B was 13,000 Yen/m^2 and 8,000 Yen /m^2, respectively (this cost includes the maintenance and repairing for the exterior wall painting and sealing and the interior gypsum plasterboard). Also, the demolition cost for both alternatives has been given a figure of 20270 Yen/m^2 for alternative A and 13514 Yen/m^2 for alternative B. These figures have been estimated by reference to historical data from similar building types from local suppliers and statistical research of Japanese home economies.

The life cycle cost has been assessed for both alternatives over 40 year's life expectancy. Additionally, the average interest rate of Japan (2.41% from 1972 until 2021) has been counted for the estimation of the costs. Regarding the availability of local building materials and labours. The majority of the raw materials in both systems are imported from outside Japan and then manufactured locally. Besides, local labours are normally hired to fix the examined façade alternatives in buildings. **Table 7-12** shows the estimated life cycle cost of the examined facades.

Façade's alternatives	Initial costs Yen/m^2	Maintenance costs Yen/m^2	Demolition costs Yen/m^2	(LCC) Yen/m^2	Raw Materials are produced locally	Locally available labours	The overall achieved points
A Hebel system	312,000	13,000	20,270	**391,106**	No	Yes	6
B Rainscreen system	200,000	8,000	13,514	**655,070**	No	Yes	0

Table 7-12: Socio-economic performance index for the alternative façade systems

The former table shows that alternative A scored higher points than alternative B in this index. Alternative A (Hebel system) has a high life expectancy and fewer maintenance cycles which proved its ability to provide the lowest overall cost and saving, thus, consider a beneficial option from an economic viewpoint. In general, the big variances in the life cycle cost between the two alternatives resulted from the fact that the expected lifetime of alternative B has a reference value of 30 years and then it is expected to reach the end of it is life before the building. Thus, after 30 years of operation, the façade is expected to be refurbished entirely, which means more cost. However, Alternative B could be valuable for use in building with a shorter life expectancy (30 years or less).

Health and well-being index (HWI)

Consistent criteria are investigated to check the role of the selected facade alternatives and their integrated materials on human health and wellbeing including chemical substances content, moisture performance, visual and thermal comfort, embodied carbon, fire performance, and acoustic performance. Regarding the hazardous chemical substances, a halogenated flame retardant (halogenated alkyl phosphate) and formaldehyde were reported with unknown percentages in the rigid polyurethane foam insulation and phenol foam insulation, respectively. However, insufficient data make it difficult to make an informed decision to determine their health impacts. Additionally, unknown substances of concerns are documented within the other integrated materials according to the data obtained from building materials manufacturers.

Moisture performance, on the other hand, has been investigated by checking four main indicators; the moisture content, the face seal and flashing details, the drained cavities, waterproofing and vapour barriers. The sealed surface of alternative A and the drained screen of alternative B are expected to divert water and moisture bulk from the façade of the detached house. However, the results showed that Alternative B scored higher points than Alternative A as an additional vapour barrier are integrated into the former.

Moreover, the solar reflectance (SR) of the innermost layers and solar reflectance index (SRI) of the outermost layers are examined to check the role of the alternatives on visual and thermal comfort. The SR of the two alternatives has the same value (85%) since the white colour gypsum plasterboard is used as the innermost finishing layer in both systems. Moreover, alternative B has a higher SRI value than alternative A in a range of 89 and 68, respectively. The Hebel panel (outermost layer of alternative A-white dove colour) has an SR and emissivity in the order of 0.58 and 0.89, while the figures ranged from 0.73

and 0.86 in the case of fibre cement siding (outermost layer of alternative B-Cream colour).

Regarding embodied carbon, alternative B scored 8 points against alternative A which scored 6 points. As mentioned previously, various factors have been examined to study the effect of the assemblies on the carbon footprint including the possibility of the façade system to be fully or partially disassembled, the use of prefabricated approach, the integration of low-carbon intensity materials or the use of supplementary cementitious materials, the use of locally-sourced materials, the durability and higher recycled content potentiality. Concerning the embodied carbon intensity, the collected data revealed that the waterproof barrier is the highest carbon coefficient material (7.4 kgCO_2/kg) while the gypsum plasterboard recorded as the lowest embodied carbon coefficient material among the investigated materials (0.38 kgCO_2/kg) (see **Table 7-13**).

Features material	Embodied Carbon Intensity (kgCO_2/kg)
Hebel panel (AAC)	0.71
Phenol insulation (NEOMA foam insulation)	2.20
Gypsum plasterboard	0.38
Fibre cement siding	1.28
Rigid urethane foam insulation	3.43
Weather-resistive barrier	6.4
Waterproof barrier	7.4

Table 7-13: embodied carbon intensity of the materials integrated into the façade assemblies

Along the same line, alternative A showed more potential to withstand fire than alternative B; their fire endurance time in an order of 60+ minutes and 45 minutes, respectively. The outermost layer of alternative A (AAC panel) has the largest participation in the overall fire-resistance rating (FRR) of the assembly. This panel is non-combustible and contains abundant air bubbles inside and innumerable pores that connect the air bubbles, thus in the event of fire these pores serve as an escape route for heat. Also, the NEOMA foam insulation is heat resistant and hard to burn. Both alternatives have been ranked as non-load bearing façade systems.

From the perspective of acoustic performance, alternative A scored higher points than alternative B; their average sound reduction is in a range of 40 dB and 30 dB, accordingly. Also, the AAC panel in alternative A provides excellent sound insulation due to its high surface mass and porous structure. Lastly, the two alternatives scored the same points on the overall health and wellbeing index (see **Figure 7-13**).

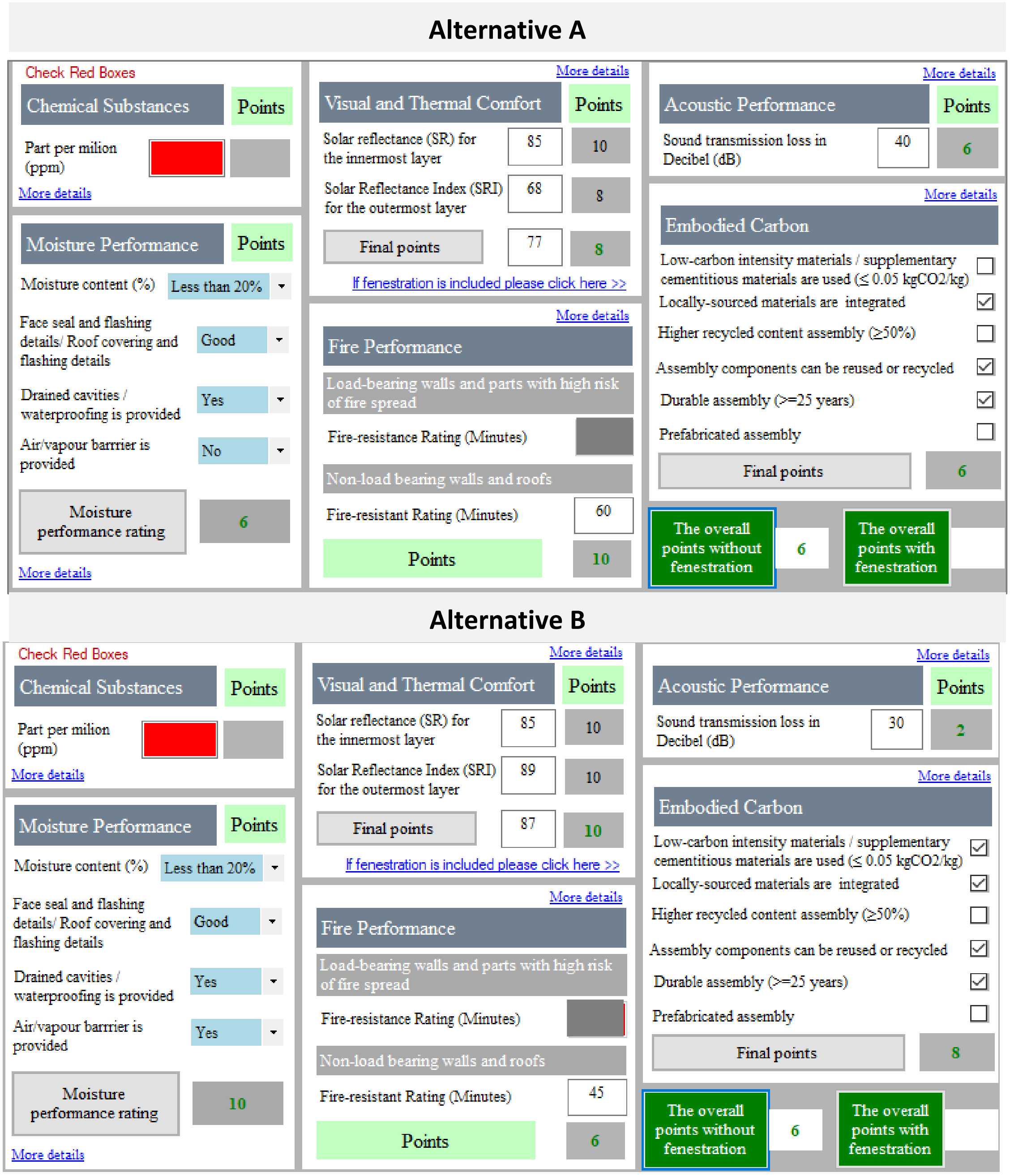


Figure 7-13: The health and wellbeing index of the assessed alternatives

Water efficiency index (WEI)

The water efficiency index of the selected façade options has been indirectly obtained by checking the embodied water coefficient of the integrated materials, the applied fixation construction techniques, and the façade disassembly approach. Concerning the embodied water coefficient, the largest water consumers per kiloliters per meter square of product are fibre cement siding (0.66 KL/m^2) and gypsum plasterboard (0.63 KL/m^2). However, these comparisons allow to know which integrated materials are responsible for the biggest water consumption, and the potential to substitute them with other alternatives that have less embodied water. The embodied water of the materials that compose the two systems are reported in **Table 7-14**.

Features material	Embodied water (KL/m^2)
Hebel panel (AAC)	0.38
NEOMA foam insulation	0.03
Gypsum plasterboard	0.63
Fibre cement siding	0.66
Rigid urethane foam insulation	0.03
Weather-resistive barrier	0.02
Waterproof barrier	0.02

Table 7-14: embodied water intensity of the materials integrated into the façade assemblies

Both alternatives scored 8 points in the final water efficiency index as shown in **Figure 7-14**. The obtained points are just benchmarks to support decision-makers in the selection of low water consumption choices. However, an in-depth analysis is required to check the mitigation strategies used for the reduction of water individually for each alternative.

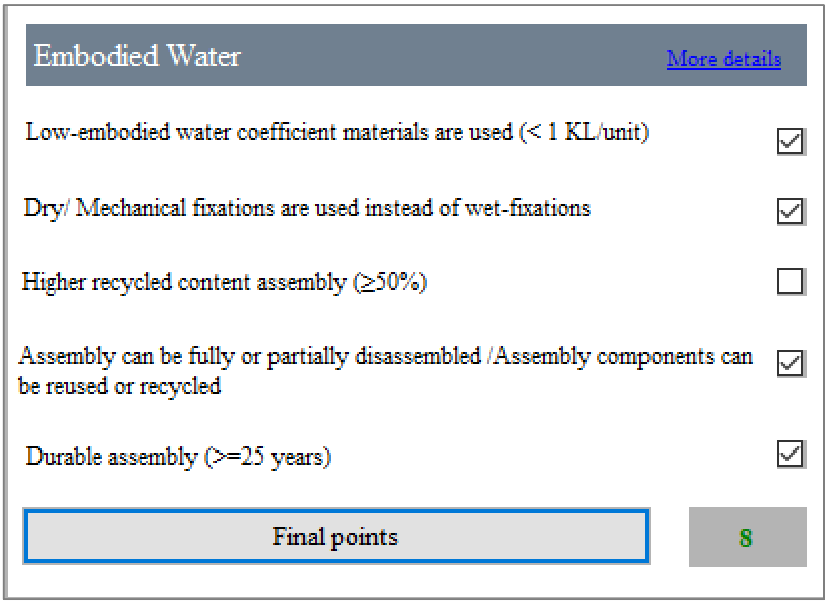


Figure 7-14: The water efficiency index of the assessed alternatives

<u>Energy efficiency index (EEI)</u>

The energy efficiency index of the selected facades has been determined by examining the total embodied energy in megajoule per square meter (MJ/m^2) and the total heat transfer coefficient in watt per square meter per kelvin (W/m^2.K). The obtained data showed that the two insulation materials (NEOMA foam and rigid urethane foam), the weather-resistive barrier and the waterproof barrier typically have larger embodied energy intensities due to the energy required for their manufacturing. The waterproof barrier has the worst embodied energy value (159 MJ/kg) among the materials integrated into the two systems. Furthermore, NEOMA foam insulation has the lowest thermal conductivity (0.020 W/m•K) makes it the most efficient and outstanding heat-resistance material. The thermophysical properties and embodied energy of the materials that compose the two systems are reported in **Table 7-15**.

Features material	**Thermal conductivity (W/m•K)**	**Density (Kg/m^3)**	**Specific heat capacity (J/(kg•K)**	**Embodied energy intensity (MJ/kg)**
Hebel panel (AAC)	0.15	600	1047	8.5
NEOMA foam insulation	0.020	27	1400	100
Gypsum plasterboard	0.22	800	840	6.75
Fiber cement siding	0.26	1380	840	15.3
Rigid urethane foam insulation	0.026	35	1400	101.50
Weather-resistive barrier	0.50	940	1555	147
Waterproof barrier	0.50	940	1555	159

Table 7-15: Thermophysical properties and embodied energy of the materials integrated into the façade assemblies

Furthermore, alternative A (the Hebel construction system) has a lower embodied energy intensity than Alternative B (the rainscreen fibre cement siding system); in the order of 559 MJ/m^2 and 1,034 MJ/m^2 respectively. Besides, the results showed that the use of thicker insulation gives rise in the embodied energy as in the case of rigid urethane foam in alternative B. See **Table 7-16**

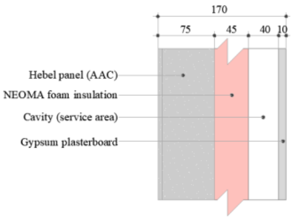
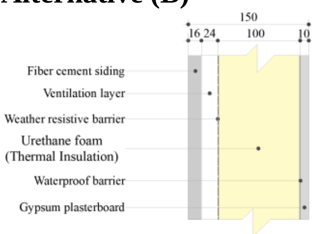
<table>
<tr><th rowspan="5">Alternative (A)

</th><th>Material/Layer</th><th>EE intensity MJ/kg</th><th>Mass kg/m^2</th><th>EE (MJ/kg× kg/m^2)</th></tr>
<tr><td>Hebel panel</td><td>8.5</td><td>45</td><td>383</td></tr>
<tr><td>NEOMA foam insulation</td><td>100</td><td>1.22</td><td>122</td></tr>
<tr><td>Cavity (service area)</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>Gypsum Plasterboard</td><td>6.75</td><td>8</td><td>54</td></tr>
<tr><td colspan="4">Total embodied energy (MJ/m^2) =</td><td>559</td></tr>
<tr><td rowspan="6">Alternative (B)

</td><td>Fiber cement siding</td><td>15.3</td><td>22.08</td><td>338</td></tr>
<tr><td>Ventilation layer</td><td>NA</td><td>NA</td><td>NA</td></tr>
<tr><td>Weather resistive barrier</td><td>147</td><td>0.94</td><td>138</td></tr>
<tr><td>Urethane foam insulation</td><td>101.50</td><td>3.5</td><td>355</td></tr>
<tr><td>Waterproof barrier</td><td>159</td><td>0.94</td><td>149</td></tr>
<tr><td>Gypsum plasterboard</td><td>6.75</td><td>8</td><td>54</td></tr>
<tr><td colspan="4">Total embodied energy (MJ/m^2) =</td><td>1,034</td></tr>
</table>

Table 7-16: Calculation of the embodied energy intensity of the two alternatives

On the other hand, the heat transfer coefficient (U-value) of alternative B was 0.23 W/m^2.K better than that of alternative A (0.32 W/m^2.K). The higher thickness of the rigid urethane foam insulation integrated into alternative B has the largest impact on the obtained value. Moreover, alternative A has a higher retention capacity than alternative B; falling in the range of 55.59 kJ/m^2.K and 33.11 kJ/m^2.K, sequentially. The Hebel panel has the highest capacity to store heat than the other materials. **Table 7-17** shows the total heat transfer coefficient and the thermal retention capacity of the selected facades systems.

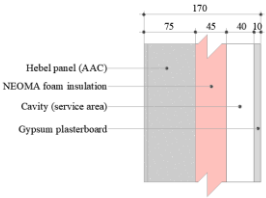
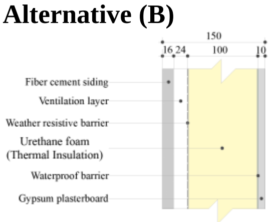
	Assembly layers	Layer width (m)	Thermal conductivity (W/m.K)	Thermal resistance (m^2.K/W)	Thermal retention capacity (kJ/m^2 K)
Alternative (A) 	Outside thermal resistance			0.04	-
	Hebel panel (AAC)	0.075	0.15	0.50	47.12
	NEOMA foam	0.045	0.020	2.25	1.70
	Cavity (Airgap)	0.040	-	0.18	0.05
	Gypsum plasterboard	0.010	0.22	0.045	6.72
	Inside thermal resistance			0.13	-
Total thermal resistance (R)				**3.145**	
Total heat transfer coefficient	**U = 1 / R = 1/3.145 = 0.32 W/m^2.K**				
Total thermal retention capacity					**55.59**
Alternative (B) 	Outside thermal resistance			0.04	-
	Fiber cement panel	0.016	0.26	0.06	18.54
	Ventilation layer	0.024	-	0.18	0.03
	Weather resistive barrier	-	-	-	1.46
	Urethane foam insulation	0.100	0.026	3.85	4.90
	Waterproof barrier	-	-	-	1.46
	Gypsum plasterboard	0.0010	0.22	0.05	6.72
	Inside thermal resistance			0.13	-
Total thermal resistance (R)				**4.31**	
Total heat transfer coefficient	**U = 1 / R = 1/4.31 = 0.23 W/m^2.K**				
Total thermal retention capacity					**33.11**

Table 7-17: Calculation of the heat transfer coefficient and thermal retention capacity of the two alternatives

Additionally, the solar reflectance index (SRI) for each façade type has been obtained by taking into account the solar reflectance and thermal emittance of the outermost facade's layers. In this regard, the Hebel panel (outermost layer of alternative A) with a white colour has an SRI of 82, while the Ivory fibre cement siding (outermost layer of alternative B) has an SRI of 75.

Moreover, the requirements of the local climate parameters of Tokyo has been estimated by using climate consultant software (version 6.0) in order to rank each alternative in terms of thermal resistance performance (See Appendix J). In general, the climate in Tokyo is temperate, with fairly mild, sunny winters and hot-humid and rainy summers. After all, the Hebel construction system scored higher points in the overall energy efficiency index than the rainscreen fibre cement siding system. See **Figure 7-15**.

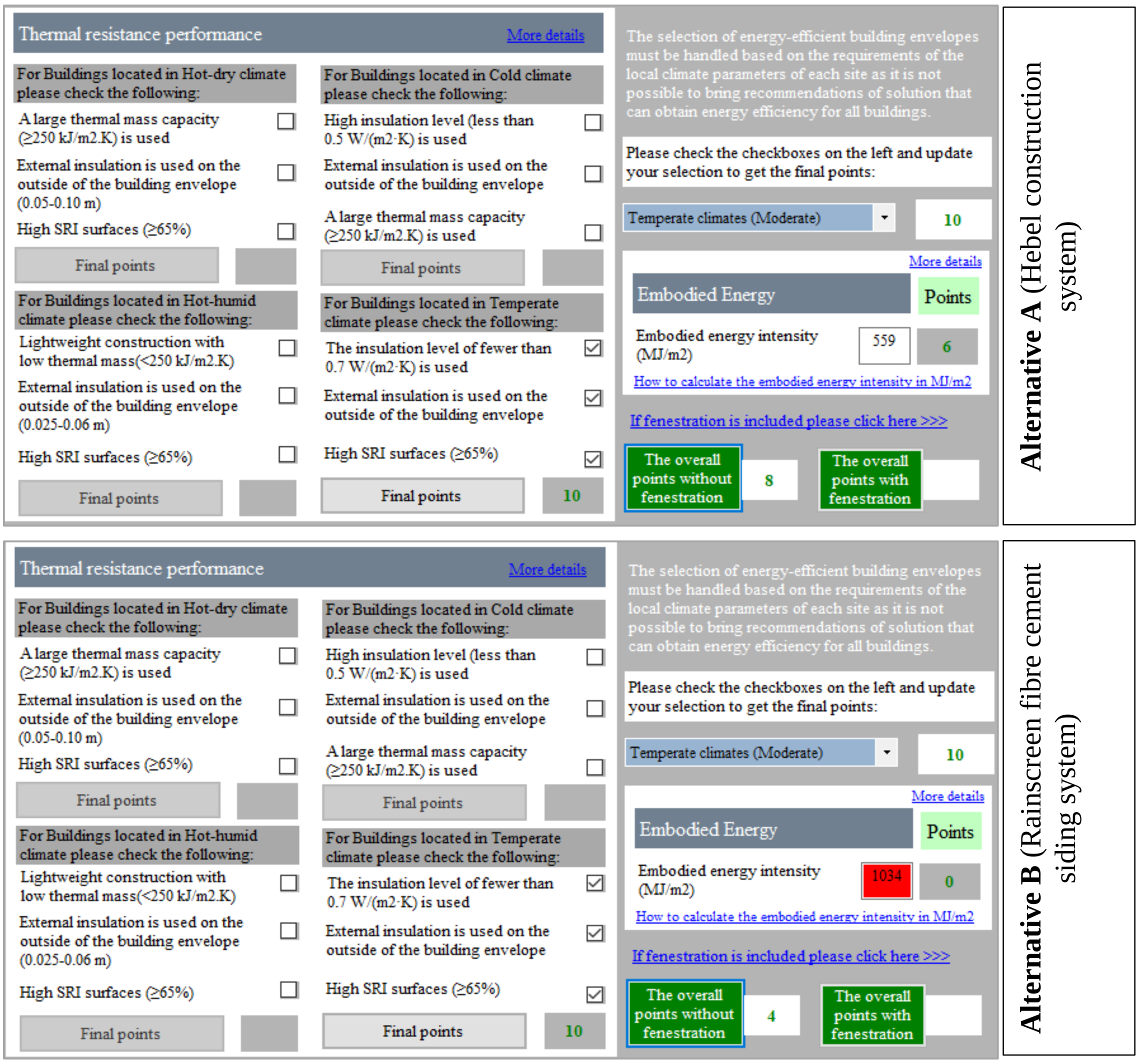


Figure 7-15: The final energy efficiency index of the selected alternatives

<u>The overall sustainability index (SI)</u>

The overall sustainability index showed that alternative A (Hebel façade system) could have a significant role in the achievement of sustainable development goals than alternative B (Rain screen fibre cement system). The final sustainability index of alternative A and alternative B attained a figure of 0.55 and 0.38 respectively. Additionally, the highest scored points are observed in the water efficiency index while the lowest scored points are noticed in the building envelope and resource efficiency index for both alternatives. Alternative A outperformed alternative B in both the socio-economic performance index and energy efficiency index (See **Figure 7-16**).

It is noteworthy that increasing the recycled content and design for disassembly are the recommended design measures that should be considered in both alternatives for achieving substantial increases in resource efficiency index and thus moving towards achieving more SDGs.

Figure 7-16: The final sustainability index of the selected facade alternatives

Furthermore, the selected façade options have been tested in several climatic conditions to see the effect of the local climatic context in the final sustainability index and to extend the use of the model. For the comparison, the materials values for the implemented criteria of both alternatives were assumed unchanged.

The results showed that alternative A predominated alternative B in all scenarios indicating its capability to be easily adapted in several regions. Also, this hypothetical analysis proved that a remarkable change in the final sustainability index would not be attained without considering a balanced approach in the whole model (in this example, the sustainability index was changed based on the changes on the energy efficiency index only). See **Figure 7-17**

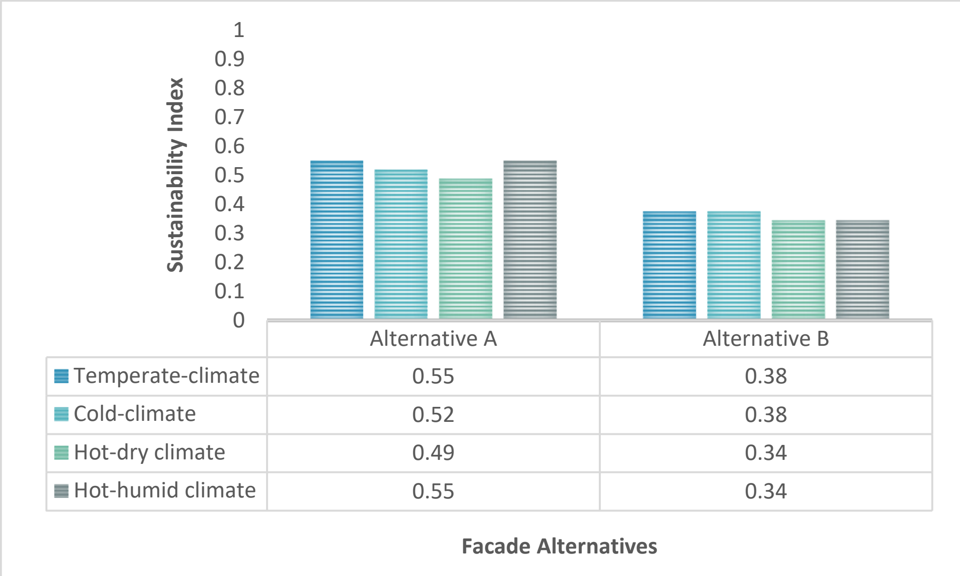


Figure 7-17: Sustainability indexes of the selected facade alternatives considering different climatic conditions

7.2 Chapter Summary

This chapter is intended to assess the sustainability index of building materials and façade assemblies of three case studies to validate the suitability and robustness of the proposed approach as well as illustrating the benefits and challenges beyond its application. Also, the strengths and weaknesses of the surveyed materials were identified to allow further investigation of the available options in the construction industry. Information on building materials was gathered through distributing questionnaires and interviews with building materials manufacturers and their related associations, engineering and construction companies, as well as reviewing existing literature (ex. published journal articles and other online electronic sources).

The results of the study proved that it is possible to apply the proposed framework to select single building materials and building envelope assemblies in real scenarios. The achieved outcome verified that the proposed tool is practical and helped to present information transparently so that is easy to report and apply for ongoing development. The findings of this chapter showed that it is possible to find a product that excels in one or two properties, but it is unlikely and difficult to define a building material or envelope that performs well in all criteria at the same time.

In most cases, even relatively small modifications in material or facade composition can bring a reduction of environmental impacts and increase the sustainability index.

However, a more constructive approach is to continue improving and creating alternatives toward raising the benchmark for sustainable building materials and assemblies. The obtained sustainability indexes highlighted that there is a wide scope for the advancement of several alternatives. These findings were predictable but not measured or stated formerly.

The conclusion of this chapter highlighted the essential need for the development of building materials and facades to overstep satisfying the minimum compliance of building codes and standards to meet the comprehensive sustainable development goals. The struggle to select alternative green building materials lies in the fact that each material is managed particularly by different manufacturers, making it hard to access detailed information about the environmental implications associated with their manufacturing to assess their sustainability. Although obtaining data for decision making requires time and effort, this is the only path to verify that the decision examines all related information.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8. CHAPTER EIGHT: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This chapter summarizes significant general findings and the most important conclusions that are presented in the previous chapters. The research aims and objectives presented in chapter one are reviewed and their realization addressed. Furthermore, it shows the research limitations and provides insights for future work.

8.1 The main findings and conclusions

In the early design stages, the benefits of integrating sustainability objectives in directing project assessments and decisions have been well highlighted. One of the major challenges is the development of a multi-criteria tool to guide designers in taking optimal material selection choices. The selection of green building materials is a complex decision-making process connecting a variety of construction stakeholders, therefore, it needs a comprehensive approach in which multiple criteria must be collectively analyzed based on a set of measures identifying environmental, socio-economic, and technical aspects of sustainability.

This research represented a framework and the demonstrative theoretical model for creating a sustainability assessment method for building materials. The model is projected to give a reference base for creating a sustainability index for material selection to enable balanced decision making and realizing sustainable development goals (SDGs). Currently, a small number of studies have considered SDGs in the construction industry and particularly in the selection of building materials and building envelope assemblies. The study intended to make a change in how the design team influencing the decision of their client's choices in building materials. The framework has the possibility to answer the following research questions:

I) Where do the products come from (product sourcing)?

II) What are they made of (ingredients/ chemicals)?

III) How long they expect to operate efficiently?

IV) How much energy and water consumed, and carbon emitted during their production process?

V) Where do they go at the end of their life (end of life strategies)?

The application of the proposed model demand substantial improvements in interdisciplinary knowledge and could be accomplished through a collaboration between several groups including the designers, contractors, building material manufacturers, users, research bodies, international governmental institutions and their states, and other non-governmental organizations.

The framework is initiated based on universal sustainable assessment criteria set to support the selection of green building materials. The criteria have been chosen to ensure that they have acceptable performance measures as well as they could be transferable and applicable among a range of alternatives irrespective of the local climatic conditions. However, the suggested method does not need the complicated and subjective pair-wise comparison (experts' previous experiences) to decide the weights of the selection criteria, hence, this model lessens such kind of individual inaccuracies that might develop due to the variations in interests, knowledge, and experiences of the engaged participants. Though, the framework enables a direct comparison between alternative building materials based on scientifically recognized criteria and materials will be selected according to their values. Furthermore, it is not feasible to optimize the performance of criteria all at once since some conflicts might appear between them. Therefore, the framework is making a balance between criteria so that the whole performance would be expanded.

Although the framework shows a simple and practical method to rank alternatives, the author believes that this study does not discuss the synergies and trade-offs which might occur among the adopted criteria in real construction practices. The trade-offs can happen even within the sub-criteria under the same group (main-criteria). The criteria are not independent and they are interrelated to the degree that decisions taken for one criterion impact the choices left for the others. The criteria overlapping is not essentially considered as a hindrance in the selection of green building materials as the trade-off between the sustainability criteria is inescapable due to their interdisciplinary nature. However, defining the acceptable limit value while defining negotiable sub-criteria could be considered a practical solution to minimize trade-offs.

Also, it should be pointed out that, criteria related to aesthetics and architectural expressions such as sight and texture are not included in this framework because they are largely subjective and difficult to quantify. Instead, criteria that could enhance the visual and thermal comfort of the users (solar reflectance of the innermost surfaces and solar reflectance index of the outermost surfaces) have been considered. These criteria could be quantified and have an explicit link with the colour and finishing of the materials.

The findings of this research proved that we are in the first phase of a long process toward identifying and producing materials that could achieve overall sustainable development. At present, it is very difficult to find materials alternatives that have a high sustainability index, partially this occurs because materials manufacturers are simply applying a few criteria when producing their products which make these alternatives not yet available on the construction market. In several instances, building material manufacture's data are not shown for the public which hinders the assessment process.

In most situations, the absence of adequate data during the extraction and manufacturing of building materials make the distinction between alternatives building materials a challenge. Furthermore, it has been noticed that the environmental impacts (ex. embodied impacts) of raw materials imported from abroad is hard to estimate and more information is needed regarding the primary fuel and energy consumed throughout the mining, extraction, preparation processes, and transportation of these materials to the production plants. This fact put more responsibility on building materials suppliers to provide such information to move towards a more transparent and sustainable supply chain.

It should be noted that, although embodied energy, embodied carbon, embodied water and related assessment are becoming more interested in the construction industry, they have not been incorporated comprehensively in the design management of the building material manufacturers. In another part, the overlap between different criteria increases the difficulty of achieving the desired goal as in many cases, having a higher sustainability index of one criterion might hinder the achievement of another. Nevertheless, developing a framework to study the correlation and trade-off between these criteria in a detailed perspective is a priority for future work.

It is important to note that, the criteria under the resource and material efficiency index (including recycled content, reusability and recyclability, design for disassembly and durability) have a direct interrelationship with almost all other implemented criteria and thus they considered a central means for determining the product's overall sustainability index. Nonetheless, it can be recommended to select materials that have higher values on these criteria to move towards achieving sustainable development goals in the remaining years. To enable the above three criteria, building materials have to be free of contaminants (hazardous substances) to be recycled and the layers within the building envelope should be assembled in an arrangement suitable to stay undamaged for disassembling and reusing; materials should be assembled in a stepwise process at the construction stage so that they could be salvaged in reverse order at the end of the building lifetime. Thus, this would suggest the need to search for further attractive strategies to enable reusing and recycling of materials with low environmental impacts and cost, and quality near to the virgin ones. These concerns should be transferred to the manufacturers so that they consider them throughout their future production.

It is worth noting that the presented framework is depending on a specific set of weightage assigned to diverse criteria; however, it gives a single index while allows decision-makers to identify the criteria with a lower index in such a way certain benchmarks could be taken to enhance their performance and sustainability. Also, it helps design teams differentiate sustainable items from greenwashed to ensure that high-performing building materials with the lowest possible environmental and health impacts are selected and thus the demand and supply for such alternatives will increase; enabling them to be affordable and readily available. Up to date, several construction products are labelled as sustainable or environmentally friendly products by their manufacturers due to the common perception that some sustainable qualities exist on them without ascertaining other satisfactory supplementary data.

In summary, the selection of building materials should be conducted paying attention to the effect of materials on the natural resources consumption, their ability to provide a high standard of indoor environmental quality, their availability and their life-cycle cost, their energy and water intensity, and the overall impact associated with their use on the environment. This research is only a provisional start to promote the selection of green building materials. The model could be used as a constructive reference to assess the performance of building materials to achieve sustainability and sustainable development goals in the construction industry. It could be advantageous for those seeking evidence-based choices on sustainable products and sustainable production.

8.2 The application of the tool/model

The proposed model simplified the sustainability assessment for material alternatives and highlighted the criteria and sub-criteria with a low-performance index to promote sustainable development. It can be utilized as a guide or stand-alone tool by building material manufacturers or other construction stakeholders who wish to enhance the sustainability of their products or choices. It can be used to assess and compare a large number of material alternatives. However, the application of the proposed model specified several particular issues of concern that can further enhance its practicability, and they can be summarized as follow:

- The proposed framework signifies the prospect of applying a composite index to integrate sustainability criteria that cannot be considered by other assessment tools, thus, filling the lack of the necessary information in the studied field.
- As previously discussed, the criteria that were harder to be assessed due to the unavailability of quality data and a standard evaluation method were embodied energy, embodied carbon, and embodied water. However, benchmark values of embodied impacts for various construction products were added, and further data is required to nationalize the tool by enabling decision-makers to select these values based on country-level and geographical location.
- The model might assist building materials manufacturers to identify ingredients in their products that they didn't even recognize as hazardous substances. Also, it will encourage competition between manufacturers to meet the criteria and integrate them into product development strategies. Thus moving towards a better quality of the entire materials process, producing more eco-friendly products, while promoting the application of the Environmental Product Declarations and Health Product Declarations.
- The application of the developed framework might help decision-makers to better understand the sustainability criteria and their boundaries (acceptable level of impacts) and provide a consistent language to distinguish between alternatives in different contexts.
- The tool evaluates the impact of the products under the specified criteria in consecutive order (one criterion after another). Thus, this offers the chance of progressing the model to evaluate the product in specific measures and does not necessarily complete the full analysis.
- The proposed tool and the schemed benchmarks are designed to be flexible and adaptable to be implemented in different countries and climatic regions to support decision making and to draw interesting international comparisons between construction products to review best practices.

8.3 Limitations and recommendation for further perspectives

The application of the model indicated that it was practically robust. However, the research carried out for this thesis has some limitations, which may inform the direction of future research. First of all, only three case studies were conducted to measure the sustainability index of several single building materials and building envelope assemblies for buildings located in one country (Tokyo-Japan); thus, while the framework initiated to be used globally, additional case studies are required to be directed in other countries for comparison with the findings from this study.

The final sustainability index of material alternatives depends mainly on the quality of the input data received from building materials manufacturers, which are often unavailable and more commercial than technical. Besides the insufficient information, there is a lack of accurate data for some criteria which make the judgment indistinct. Thus, an effort is needed to ensure that the collected data are validated by a third party to verify any claims that are made and to ensure the consistency of the obtained sustainability indexes.

Furthermore, further steps are needed to create a comprehensive database for building materials that could be linked directly with the manufacturers to share the necessary information regarding their products in a standardized format. This step indeed will advance the model into a web-based platform to make material's data readily accessible, reducing time and cost, while encouraging transparency in the construction industry.

The sub-criteria have been assigned to an equal weight to achieve the final sustainability index of each main criteria. However, the proposed weightage system may not conform to the priorities of all stakeholders. Thus, more exploration is required to show the priority of the assigned sub-criteria in the final weight of main-criteria indexes.

After the development of the case studies, the following research work is needed to enhance the practicability and feasibility of the proposed tool and framework:

- Future case studies should be conducted to show the practicability of using a complete façade system including the solid part and fenestration so that a variety of construction decisions could be made by utilizing the system.
- The obtained outcomes showed that the boundary conditions of the proposed model could be extended to other building typologies (ex. commercial and educational buildings) and building components (ex. structural members). This

could be achieved by examining all the sustainability concerns linked to the new building typology and deciding the need to introduce extra criteria and adjusting their relevant weight with the overall aim of achieving SDGs.

- The life cycle assessment boundary for the material's embodied impacts could be extended from cradle to gate to cover the construction process stage, operation and maintenance stages, and end of life stage. Additionally, further analysis is required to evaluate the life cycle energy costs of building envelope assemblies concerning their energy efficiencies (reduced operational costs) taking into consideration the discount rate and time.
- Further efforts are required to integrate the proposed tool into Building Information Modelling (BIM) software to assist the selection of optimum building materials from the preliminary design stages. This could enable users to design and evaluate their alternatives using one single model.
- Further investigation is required to show the possibility of integrating other parameters (criteria) into the tool such as the façade's geometry, orientation, and the external shading system alongside the applied criteria for further optimization to the energy performance of the building envelope assemblies.
- Research is needed to explore the possibility of adjusting the weight of the main and sub-criteria based on the preferences (experience) of the decision-makers (involved stakeholders) to respond to the needs of their particular product and to make a comparison with the proposed weightage system.

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APPENDICES

Appendix A: Examples of Life-Cycle Assessment and Life-Cycle Inventory Tools

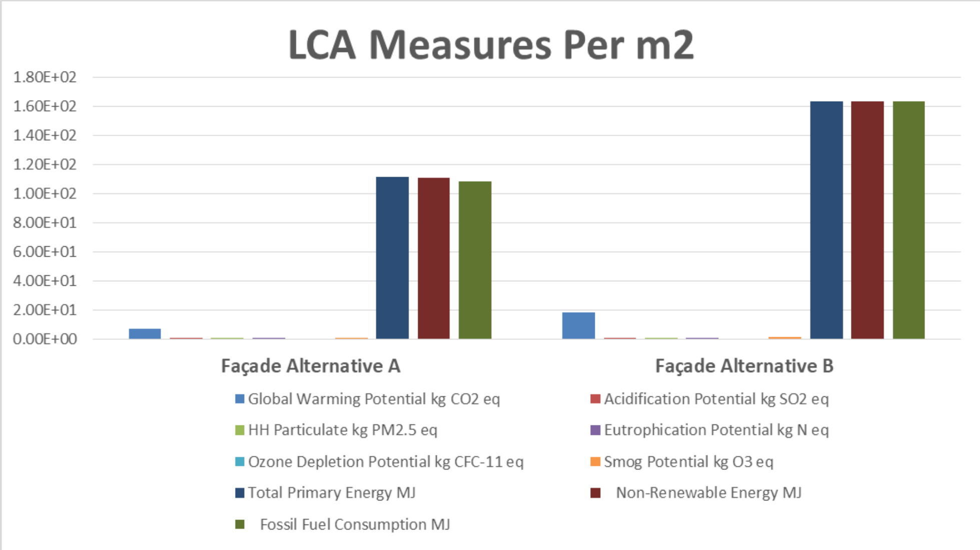


Figure A-1: Comparison of LCA measures in Athena IE for two façade alternatives

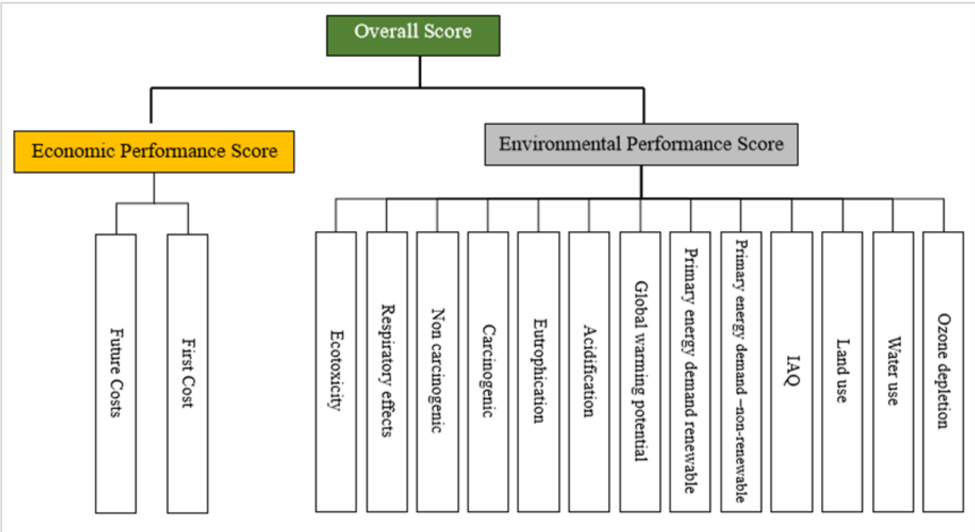


Figure A-2: BEES Online 2.0 Model

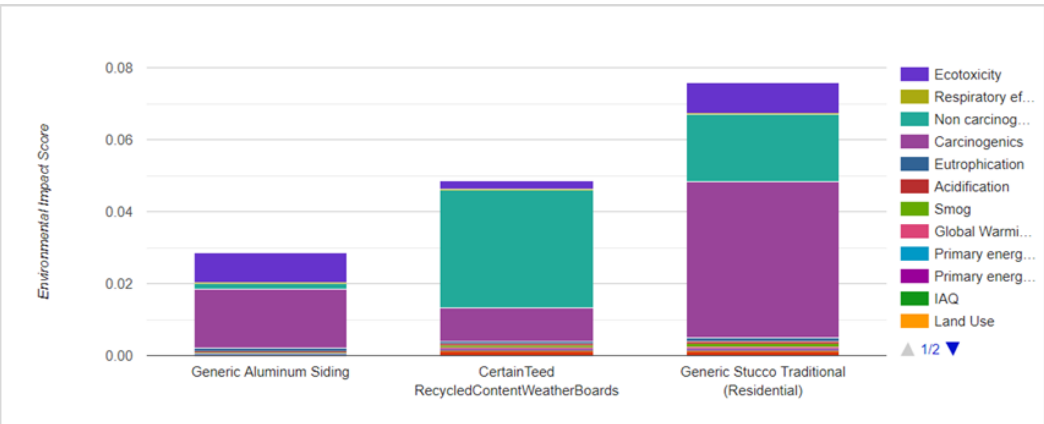


Figure A-3: Example of Environmental Impact Scores across products in BEES

Appendix B: The contribution of building materials on the achievement of SDGs

GOAL 1: END POVERTY IN ALL ITS FORMS EVERYWHERE			
Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	Reference(s)
1.4	Encouraging the utilization of local materials will reduce the properties construction cost, also affording homes with access to basic services and local technology.	+2	(Ahmad et al., 2019; Bredenoord & van Lindert, 2010; Celentano et al., 2019; Isnin et al., 2013; Ugochukwu & Chioma, 2015)
1.5	The use of local materials can offer people the opportunity to build their own homes which reduce their exposure and vulnerability to extreme external environmental disasters.	+2	

GOAL 3: ENSURE HEALTHY LIVES AND PROMOTE WELL-BEING FOR ALL AT ALL AGES			
Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
3.4	The use of green, alternative, environmentally safe, and responsibly sourced building materials can prevent users of the building from diseases of long duration and low progression like lung diseases, damage to the liver and central nervous system, which associated with volatile organic compounds emitted into the air from some building materials.	+3	(Bartzis et al., 2008; Bragança et al., 2010; Building 2030, 2017; Cai & Sun, 2014; Corvalán & Üstün, 2006; D & M S, 2018; FUCIC, 2012; Huberman & Pearlmutter, 2008; Y. M. Kim et al., 2001; Kubba, 2010; Passarelli, 2009; Patil & Patil, 2017; Petrovic´ et al., 2017; Sandanasamy et al., 2011; Spiegel & Meadows, 2010; Steinemann, Wargocki, & Rismanchi, 2017; Y. Sun et al., 2019; World Health Organization (WHO), 2016b; Xu Zhang et al., 2018)
3.9	Green, alternative, environmentally friendly, and responsibly sourced building materials can provide a better indoor healthy environment for human being and minimize the health impacts for the users of the building.	+3	

GOAL 4: ENSURE INCLUSIVE AND EQUITABLE QUALITY EDUCATION AND PROMOTE LIFELONG LEARNING OPPORTUNITIES FOR ALL			
Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
4.7	Introducing the importance of using green and alternative building materials to support sustainable development through education systems will be key to achieving the UN 2030 Agenda and promote a sustainable lifestyle for the next generations.	+1	(Schmidt et al., 2017; Sichali & Banda, 2017; Umar et al., 2009)

GOAL 6: ENSURE THE AVAILABILITY AND SUSTAINABLE MANAGEMENT OF WATER AND SANITATION FOR ALL

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
6.3	The utilization of responsibly sourced building materials reduce pollution, minimize the release of hazardous chemicals and improve the quality of water in buildings.	+2	(Abd El-Hameed, 2018; Bardhan, 2011; Das et al., 2015; Heravi & Abdolvand, 2019; Sheth, 2017; World health organization, 2010)
6.4	Increasing the use of green, alternative, environmentally safe, and responsibly sourced building materials reduce water consumption in the construction sector.	+2	

GOAL 7: ENSURE ACCESS TO AFFORDABLE, RELIABLE, SUSTAINABLE AND MODERN ENERGY FOR ALL

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu - Score	References
7.3	The use of durable, green, energy-efficient, alternative and low embodied building materials save energy in the buildings and serve to achieve SDGs.	**+3**	(Peter O. Akadiri et al., 2012; Asif et al., 2007; Basbagill et al., 2013; Cai & Sun, 2014; Dixit, 2019; Dodoo et al., 2012; Huberman & Pearlmutter, 2008; Macaluso, 2010; Morel et al., 2001; Mpakati-Gama et al., 2012; S. Ramesh, 2011; Rauf & Crawford, 2015; Reddy & Jagadish, 2003; Shams et al., 2012; Singh et al., 2015; Thormark, 2006; Venkatarama Reddy, 2009; Zabalza Bribián et al., 2011; L. Zhu et al., 2009)

GOAL 8: PROMOTE SUSTAINED, INCLUSIVE AND SUSTAINABLE ECONOMIC GROWTH, FULL AND PRODUCTIVE EMPLOYMENT AND DECENT WORK FOR ALL

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu - Score	References
8.4	The innovation in building materials industry and technology can lead to higher productivity and more efficient use of raw material resources	**+2**	(Liming, 2011; WGBC, 2017)
8.5	The demand for green and alternative building materials have been accompanied by employing many people from various disciplines, which reflect the impact of building materials in the promotion of economic growth and employment.	**+1**	

GOAL 9: BUILD RESILIENT INFRASTRUCTURE, PROMOTE INCLUSIVE AND SUSTAINABLE INDUSTRIALIZATION AND FOSTER INNOVATION

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
9.1	The development of sustainable and resilient infrastructure is connected directly by using green and advanced building materials for the construction of these facilities. Additionally, the use of durable materials for the construction of different infrastructures will ensure the quality and the durability of our infrastructure worldwide.	+3	(Balasbaneh et al., 2019; Hossain, 2015; Pour-Ghaz, 2013; Schlangen & Sangadji, 2013; H. C. Wu, 2006)
9.4	The innovation in building materials industry will upgrade the development of adaptable, cost-effective and green infrastructure which can face the global challenges of climate change and future risks	+3	

GOAL 11: MAKE CITIES AD HUMAN SETTLEMENTS INCLUSIVE, SAFE, RESILIENT AND SUSTAINABLE AGES

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
11.1	Using locally available and alternative building materials for housing can reduce both the construction cost and the building's impact on the environment.	+2	(Akande et al., 2019; Balaban & Puppim de Oliveira, 2017; Bibri & Krogstie, 2017; Bredenoord, 2017; Giles-Corti et al., 2019; J. Han et al., 2017; J, 2015; Kayode & Olusegun, 2013; Port, 2007; B. N. Silva et al., 2018; Steverson & Steverson, 2018; United Nation-UN, 2014)
11.6	Buildings are the foundations of cities and communities, therefore selecting green, alternative environmentally safe, and responsibly sourced building materials are key to their long-term sustainability.	+3	

GOAL 12: ENSURE SUSTAINABLE CONSUMPTION AND PRODUCTION PATTERNS

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
12.2	Green and responsibly sourced building materials which are produced from local supplies achieve efficient utilization of natural resources.	+3	(Cai & Sun, 2014; Kralj & Markič, 2008; Ng & Chau, 2015; J. Park et al., 2017)
12.4	Building materials with green features are considered ecological, non-hazardous, non-polluting and non-radioactive materials. The use of these materials will achieve a healthy environment for human and minimize the negative effect of building on the built environment.	+3	

12.6	The use of green building materials has already encouraged companies and construction stakeholders to implement sustainability in various projects all over the world.	+1	
12.7	The building materials industry play a major role in promoting sustainable public procurement, through supporting the use of green building materials for various construction practices to minimize the environmental impacts and by encouraging the use of environmental assessments tools to evaluate their effects.	+1	

GOAL 13: TAKE URGENT ACTION TO COMBAT CLIMATE CHANGE AND ITS IMPACTS

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
13.1	Building materials have a huge capability to mitigate the impact of buildings in the global greenhouse gases emissions and other climate-related hazards through the use of energy-efficient, green, environmentally friendly and alternative building materials.	+3	(Andersson-sköld et al., 2015; B. Huang et al., 2018; Klijn-Chevalerias & Javed, 2017; Najjar et al., 2017; Sagheb et al., 2011)
13.2	Various environmental assessment measures and tools have been created and employed to measure all inputs and outputs of the building materials throughout their lifetime. Many countries integrated them into their national policies and strategies. However, by supporting and encouraging the use of these tools and strategies all over the world a great achievement will be noticed regarding SDGs.	+1	

GOAL 14: CONSERVE AND SUSTAINABLY USE THE OCEANS, SEAS AND MARINE RESOURCES FOR SUSTAINABLE DEVELOPMENT

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
14.1	The use of alternative Building Materials that do not contain harmful ingredients to achieve the sustainability of marine ecosystems.	+1	(Perkins and Will Architects, 2016; Petrović, Vale, Zari, & Zari, 2017)

GOAL 15: PROTECT, RESTORE AND PROMOTE SUSTAINABLE USE OF TERRESTRIAL ECOSYSTEMS, SUSTAINABLY MANAGE FORESTS, COMBAT DESERTIFICATION AND HALT AND REVERSE LAND DEGRADATION AND HALT BIODIVERSITY LOSS

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
15.1	The promoting of responsibly sourced, green, and alternative materials is a key element to achieve sustainability and to ensure better conservation of resources.	+2	(Bloodworth et al., 2009; Fugiel et al., 2017; Opoku, 2019; Sahu & Dash, 2011)

15.3	The use of responsibly sourced building materials for construction practices can play a major role to combat desertification and restore degraded land and soil.	**+3**	
15.5	The encouraging use of responsibly sourced building materials can have a major role to preserve biodiversity and natural habitats.	+3	

GOAL 17: STRENGTHEN THE MEANS OF IMPLEMENTATION AND REVITALIZE THE GLOBAL PARTNERSHIP FOR SUSTAINABLE DEVELOPMENT

Relevant Sustainable Development Targets	Key Contributions (examples)	Best Contribu-Score	References
17.16	The development in the building materials industry will lead to a significant process to strengthen the partnership between construction stakeholders to support the achievement of sustainable development goals in all countries.	+1	(Nußholz, Nygaard Rasmussen, et al., 2019)

Table B1: The contribution of building materials in the achievement of sustainable development goals and targets

Material	**Recycled Content**		**Material Value ($)**	**Recycled Content Value ($)**
	Post-consumer (%)	Pre-consumer (%)		
Concrete foundation and floors	8	2	120,000	10,800
Steel columns, beams, studs	40	0	400,000	160,000
Gypsum board	50	10	60,000	33,000
Insulation	80	0	8,000	6,400
Brick	16	0	65,000	10,400
Mortar	4	0	12,000	480
Carpet	16	60	50,200	23,092
Fenestration and doors	10	10	320,000	48,000
Roofing	0	0	35,000	-
Ceiling	80	0	6,000	4,800
Total Value			**1,076,200**	**276,972**
Total Recycled Content percentage				**23,74%**

Table B2: Calculation of a building's recycled content based on LEED

Appendix C: The promising criteria adopted to achieve sustainable development goals and targets

Sustainable development goals and targets	How to achieve the goal/target through construction and building materials? (key contributions)	The linked main criteria	Promising sub-criteria (indicators)	Reference (s)
Goal 1. End poverty in all its forms everywhere				
1.4 By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance.	- Encouraging the utilization of local materials will reduce the properties construction cost, also affording homes with access to basic services and local technology. - Increased use of local resources (labour and materials) will improve access to income and employment opportunities and further motivating the local economy.	- Socio-economic Performance (SEP)	- locally available materials - locally available labours - initial costs	(Ahmad et al., 2019; Bredenoord & van Lindert, 2010; Celentano et al., 2019; Isnin et al., 2013; Karnani, 2011; Ugochukwu & Chioma, 2015)
1.5 By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters.	- Achieving this target requires upgrading and constructing new infrastructures by implementing local and durable building materials to reduce and mitigate exposure to climate-related disasters.	- Resource and material efficiency (RME) - Socio-economic Performance (SEP)	- Durability - locally available materials - locally available labours	
Goal 3. Ensure healthy lives and promote well-being for all at all ages				
3.4 By 2030, reduce by one-third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being.	- Responsibly sourced building materials can prevent users of the building from diseases of long duration and low progression associated with mould and volatile organic compounds emitted into the air from some building materials. - The occupant’s well-being is directly linked to indoor air quality, acoustic comfort, fire performance, and thermal and visual aspects.	- Health and well-being impact (HW)	- Red list materials - Embodied carbon - Moisture content - Acoustic performance - Fire-resistant performance - Visual and thermal comfort	(Al Horr et al., 2016; Bartzis et al., 2008; Bragança et al., 2010; Building 2030, 2017; Cai & Sun, 2014; Corvalán & Üstün, 2006; D & M S, 2018; FUCIC, 2012; Huberman & Pearlmutter, 2008; Y. M. Kim et al., 2001; Kubba, 2010; Passarelli, 2009; Patil & Patil, 2017; Petrovic´ et al., 2017; Sandanasamy et al., 2011; Spiegel & Meadows, 2010; Steinemann et al., 2017; Y. Sun et al., 2019; World Health Organization (WHO), 2016b; Xu Zhang et al., 2018)
3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.	- Building materials can provide a better indoor healthy environment for human being and minimize the health impacts for the users of the building.		- Red list - Embodied carbon - Moisture content	
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all				
4.7 By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and culture’s contribution to sustainable development.	- The application of healthy building materials which produce from local resources and can withstand harsh climatic conditions will promote lifelong education opportunities for all.	- Health and well-being impact (HW) - Resource and material efficiency (RME) - Socio-economic Performance (SEP)	- Red list materials - Durability - Locally available materials	(Schmidt et al., 2017; Sichali & Banda, 2017; Umar et al., 2009)

Goal 6. Ensure availability and sustainable management of water and sanitation for all				
6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.	- Building materials that do not contribute to water contamination should be selected.	- Health and well-being impact (HW)	- Red list materials	(Abd El-Hameed, 2018; Bardhan, 2011; Das et al., 2015; Heravi & Abdolvand, 2019; Sheth, 2017; World health organization, 2010)
6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.	- Increasing the use of low embodied-water building materials reduce water consumption while increase water efficiency.	- Water Efficiency (WE)	- Embodied water	
Goal 7. Ensure access to affordable, reliable, sustainable and modern energy for all				
7.3 By 2030, double the global rate of improvement in energy efficiency.	- The use of durable, energy-efficient, and low embodied building materials save energy in the buildings and serve to achieve SDGs. - The selection of appropriate materials by determining their thermal characteristics has the highest potential to improve energy performance of the buildings.	- Energy Efficiency (EE)	- Embodied energy - Thermal conductivity - Specific heat capacity - Density	(Peter O. Akadiri et al., 2012; Asif et al., 2007; Basbagill et al., 2013; Cai & Sun, 2014; Dixit, 2019; Dodoo et al., 2012; Huberman & Pearlmutter, 2008; Macaluso, 2010; Morel et al., 2001; Mpakati-Gama et al., 2012; S. Ramesh, 2011; Rauf & Crawford, 2015; Reddy & Jagadish, 2003; Shams et al., 2012; Singh et al., 2015; Thormark, 2006; Venkatarama Reddy, 2009; Zabalza Bribián et al., 2011; L. Zhu et al., 2009)
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all				
8.4 Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead	- Achieving this target requires the implementation of higher recycled contents materials, reusing and recycling of construction waste, and using durable materials. - An increased use of local resources (labour and materials) will improve access to income and employment opportunities and further motivating the local economy.	- Resource and material efficiency (RME) - Socio-economic Performance (SEP)	- Recycled content - Reusability and recyclability - Durability - locally available materials - locally available labours	(Karnani, 2011; Liming, 2011; WGBC, 2017)
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation				
9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and trans-border infrastructure, to support economic development and human well-being, with a focus on affordable and equitable access for all.	- The development of sustainable and resilient infrastructure is connected directly by using responsibly-sourced materials for the construction of these facilities. Additionally, the use of durable materials will ensure the quality and the stability of our infrastructure worldwide. - Using local labours and materials helps to create sustainable infrastructure and support local economic growth. - Applying construction materials with low-embodied energy and low embodied water will create more sustainable and resilient infrastructure.	- Health and well-being impact (HW) - Resource and material efficiency (RME) - Socio-economic Performance (SEP) - Water Efficiency (WE) - Energy Efficiency (EE)	- Red list - Recycled content - Reusability and recyclability - Durability - locally available materials - locally available labours - Embodied water - Embodied energy	(Balasbaneh et al., 2019; Hossain, 2015; Leo Samuel et al., 2017; Pour-Ghaz, 2013; Schlangen & Sangadji, 2013; H. C. Wu, 2006)

9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.	- This target can be achieved by utilizing healthy and resource-efficient building materials. - Cutting embodied energy, carbon, and water in construction projects is a key to upgrade infrastructures and make them sustainable.	- Resource and material efficiency (RME) - Health and well-being impact (HW) - Water Efficiency (WE) - Energy Efficiency (EE)	- Recycled content - Reusability and recyclability - Durability - Red list - Embodied carbon - Embodied water - Embodied energy	
Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable				
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.	- Using locally available building materials and labours for constructing housing can reduce both the construction cost and the building's impact on the environment.	- Socio-economic Performance (SEP)	- locally available materials - locally available labours - initial cost - Maintenance and replacement cost - Demolition cost	(Akande et al., 2019; Balaban & Puppim de Oliveira, 2017; Bibri & Krogstie, 2017; Bredenoord, 2017; Giles-Corti et al., 2019; J. Han et al., 2017; J, 2015; Kayode & Olusegun, 2013; Morini, Ribeiro, & Hotza, 2019; Port, 2007; B. N. Silva et al., 2018; Steverson & Steverson, 2018; United Nation-UN, 2014)
11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.	- Applying recycled content materials and using reusability, recyclability, and durability approaches will reduce the construction waste and pollution while playing a direct role in achieving this target. - Buildings are the foundations of cities and communities, therefore selecting environmentally safe, responsibly-sourced, and durable building materials are key to their long-term sustainability. - Using locally available building materials can reduce the construction cost, minimize the negative impacts of the buildings on the environment. - The embodied energy and carbon footprint of building materials can be reduced by utilizing ecologically benign materials.	- Resource and material efficiency (RME) - Socio-economic Performance (SEP) - Health and well-being impact (HW) - Water Efficiency (WE) - Energy Efficiency (EE)	- Recycled content - Reusability and recyclability - Durability - locally available materials - Red list - Embodied carbon - Embodied water - Embodied energy	
Goal 12. Ensure sustainable consumption and production patterns				
12.2 By 2030, achieve the sustainable management and efficient use of natural resources.	- The building industry is one of the largest consumers of natural resources, therefore, using green and responsibly sourced building materials produced from local supplies will enable the efficient utilization of natural resources. - The utilization of durable building materials is key to sustainable consumption, as their use gives precedence to minimizing the amount of materials resources employed and waste produced.	- Resource and material efficiency (RME) - Socio-economic Performance (SEP) - Energy Efficiency (EE) - Water Efficiency (WE)	- Recycled content - Reusability and recyclability - Durability - locally available materials - Embodied energy - Embodied water	(Cai & Sun, 2014; Kralj & Markič, 2008; Ng & Chau, 2015; J. Park et al., 2017)
12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce	- Building materials with green features are considered ecological, non-hazardous, non-polluting and non-radioactive materials. The use of these materials will achieve a healthy environment for	- Health and well-being impact (HW)	- Red list - Recycled content - Reusability and recyclability	

their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	human and minimize the negative effect of building on the built environment.	- Resource and material efficiency (RME)	- Durability	
12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.	- Applying the three R's of waste management which comprise reduce, reuse and recycle; helping to conserve natural resources, landfill space, energy, as well as cutting down the amount of construction waste. - The sustainability of buildings is a function of their durability; the longer a building material stays in operation, the lesser the consumption of natural resources are per year of service.	- Resource and material efficiency (RME)	- Recycled content - Reusability and recyclability - Durability	
Goal 13. Take urgent action to combat climate change and its impacts				
13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.	- Durable building materials are required for the construction of new shelters and emergency facilities which increase the resilience of places that are susceptible to the effects of climate change disasters. - Building materials have a huge capability to mitigate the impact of buildings in the global greenhouse gases emissions and other climate-related hazards through the use of energy-efficient, green, environmentally friendly and alternative building materials.	- Resource and material efficiency (RME) - Energy Efficiency (EE) - Health and well-being impact (HW) - Water Efficiency (WE)	- Durability - Embodied energy - Embodied carbon - Embodied water	(Andersson-sköld et al., 2015; B. Huang et al., 2018; Klijn-Chevalerias & Javed, 2017; Najjar et al., 2017; Sagheb et al., 2011)
Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development				
14.1 By 2025, prevent and significantly **reduce marine pollution of all kind**s, in particular **from land-based activities**, including marine debris and nutrient pollution.	- The use of alternative building materials that do not contain harmful ingredients can achieve the sustainability of marine ecosystems. - Applying the 3R's of waste management when selecting building materials will reduce construction waste and consequently decrease marine pollution.	- Health and well-being impact (HW) - Resource and material efficiency (RME)	- Red list - Recycled content - Reusability and recyclability - Durability	(Perkins and Will Architects, 2016; Petrović, Vale, Zari, & Zari, 2017)
Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss				
15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world.	- The promoting of responsibly sourced, green, and alternative materials is a key element to achieve sustainability and to ensure better conservation for resources.	- Resource and material efficiency (RME)	- Recycled content - Reusability and recyclability - Durability	(Bloodworth et al., 2009; Fugiel et al., 2017; Opoku, 2019; Sahu & Dash, 2011)
15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species.	- The encouraging use of responsibly sourced building materials can have a major role to preserve biodiversity and natural habitats.	- Resource and material efficiency (RME)	- Recycled content - Reusability and recyclability - Durability	

Table C1: The possible material criteria to achieve sustainable development goals and targets

Appendix D: The reliant main criteria and sub-criteria for envelope evaluations

Main Criteria	Sub-criteria	Reference
Thermal performance	Heat transfer coefficient of roof	(Zheng et al., 2010)
	Heat transfer coefficient of ground	
	Heat transfer coefficient of external wall	
	Heat transfer coefficient of the windows	
	Heat transfer coefficient of door	
Building form	Maximum form coefficient	
	Perfect form coefficient	
	Orientation	
	Floor to ceiling height	
	Window-to-wall ratio	
	Shading coefficient of window glass	
Economy	Initial construction costs	
	Maintenance costs	
Innovation	New technology	
	New material and product	
Reliability	Safety	
	Comfort	
	Durability	
Environmental protection	Environmental protection	
Environmental Impact efficiency	Renewable resources depletion	(Iwaro & Mwasha, 2013; Iwaro et al., 2014)
	Non-renewable resources depletion	
	Deforestation	
	Indoor air quality	
	Air pollution	
	Noise pollution	
	Material emission	
	Construction waste	
	Energy consumption (GJ)	
	Carbon emission (kg/50yrs)	
	Indoor health impact	
	Water pollution	
	Sanitation effect	
	Volatile organic chemical	
	Climate change	
	Ozone depletion	
	Biodiversity impact	
	Toxicity of materials	
Energy efficiency	Building Envelope design	
	Energy conservation	
	Energy consumption	
	Equipment and appliance	
	Wall insulation	
	Embodied energy (MJ)	
	Renewable resources depletion	
	Non-renewable resources depletion	
	Door and window frame	
	Operation energy (GJ/50yrs)	
	Window and door glazing	
	Labelling and certification	
Material efficiency	Low pollution effect	
	Low toxic materials	
	Embodied energy	
	Minimal emission	

Main Criteria	Sub-criteria	Reference
Material efficiency	Indoor air quality	(Iwaro & Mwasha, 2013; Iwaro et al., 2014)
	High moisture resistance	
	Material life span	
	Low maintenance	
	Durability	
	Minimum heat gain	
	Minimum material waste	
	Natural material	
	Minimum risk effect	
	Energy-saving potential	
	Renewable potential	
	Recycling potential	
	Minimum hazardous demolished waste	
	Minimum hazardous materials	
	Energy-saving potential	
External Benefit	Environmental ecological value	
	Environmental economical value	
	Local community economic	
	Landscape beautification	
	Environmental beautification	
	User productivity	
	Indoor air quality	
	Living environment	
	Indoor environment	
	Social image	
	Tourism patronage	
	Natural habitat	
	Employment opportunity	
	Heritage preservation	
	Envelope appearance	
Regulation efficiency	Regulation compliance	
	Moisture resistant	
	Airtightness	
	Energy consumption (GJ)	
	Heat loss/gain	
	Design flexibility	
	Environmental performance	
	Energy subsidies	
	Construction quality	
	Carbon emission (kg/50yrs)	
Economic Efficiency	Pre-construction cost/GFA ((TT$/sf)	
	Construction cost/GFA (TT$/sf)	
	Operating cost/GFA (TT$/sf)	
	Maintenance cost/GFA (TT$/sf)	
	Residual cost/GFA (TT$/sf)	
Environmental impacts	Global warming potential	(Huedo et al., 2016)
Use of resources	Primary energy consumption	
	Water consumption	
Complementary environmental information	Non-hazardous waste	
	Hazardous waste	
Economic indicator	Investment costs	
	Maintenance costs	
	Energy costs	

Main Criteria	Sub-Criteria	Reference
Environmental impacts	Embodied energy and carbon emissions	(Moussavi Nadoushani et al., 2017)
	Heating load	
	Cooling load	
	Resource sustainability	
Life cycle cost	Material cost	
	Labour cost	
	Transport cost	
	Maintenance cost	
	Design cost	
Performance	Weight	
	Thermal resistance	
	Thermal mass	
	Acoustic insulation	
	Resistance to decay	
Social benefits	Aesthetics	
	Suitability to location	
	Suitability to climate	
Qualitative Criteria	**Quantitative-Criteria**	**Reference**
Structural Performance	U-value	(Kyriakidis et al., 2019)
Assembly and Disassembly	Time lag	
Ease of Construction	Decrement Factor	
Construction Time	Embodied Energy/Carbon	
Reusability and Recyclability		
Need for Maintenance		
Architectural Expression		

Table D1: previous studies concerning the multi-criteria optimization of building envelopes assemblies and materials.

Appendix E: Building materials survey questionnaire samples.

I: The selection of single building materials

Development of a multi-criteria optimization approach for the selection of green building materials 環境配慮型建材の選択における多基準最適化手法の開発 Building Type: Residential/Office Building						
1. Material Name **材料の名前**				○ Structural構造用 ** 当てはまる方を選んで下さい*		◉ Non-structural非構造用
2. General Description **概要（差し支えない範囲で材質や用途など）**						
3. Percentage recycled content (%) **リサイクル率（体積%）**	Pre-consumer 廃棄物等を使用している割合			Post-consumer 供用後にリサイクルできる割合		Total recycled content 全体のリサイクル率
4. The expected life time (Years) **設計寿命 (年)**						
5. Requirements **要求条件** **(Years)** **（年）**	Need Maintenance /Repairing維持・修理 *修理・維持の時期・回数について教えてください。*			Need Replacement交換 *交換時期・回数について教えてください。*		
6. End-of-life strategies **供用終了後の戦略** ** 付表の定義をご覧ください*	Reusable 再利用性	Renewacyclable 再利用・リサイクル可能な原料を用い、環境を汚染することなく廃棄できる。	Recyclable リサイクル性	Semi-reusable 半再利用性。物理的・科学的に変化は少ないがもとの性能を損なっており、元とは違う用途で使われる。	Semi-recyclable 半リサイクル性。リサイクルできるがもとの性能を損なっており、元と同じ用途で使われるとは限らない。	Non-recyclable or Non-renewable Material 再利用、リサイクルできない
** 当てはまるものに〇をつけて下さい*	○	○	○	○	○	○
7. Availability of materials and labours locally **現地で材料、労働力が生産・調達できるか**	Is the material produced locally? 材料が現地で生産・調達できるか			Are there available local labours to fix this material into buildings? 材料を扱える労働力を現地で用意できるか		
** 当てはまるものに〇をつけて下さい*	○ Yes	○ No		○ Yes	○ No	
8. Life cycle cost (LCC) **ライフサイクルコスト**	Initial cost ($) 生産コスト	Maintenance cost ($) 修理・維持コスト		Replacement cost ($) 交換コスト	Demolition cost ($) 解体コスト	
** US ドルに換算をお願いいたします。*						
9. Red List / Chemical avoidance list **有害な化学物質**	Are there any specific chemical substances found in this material? 何らかの制限のある有害な化学物質を含有していますか？ *(please check the attached common hazardous list)* *（添付の有害物質リストをご確認ください）* ○ Yes			○ No		
If yes, please specify the type and percentage *含有している場合、その割合*		*The weight of the hazardous chemicals in a certain material can be explained as ppm (part per million)* *有害物質の重量割合（%）（いくつかの有害物質では単位ppm）*				
Please specify the Current technology the company might developed to mitigate the impact on health and environment (especially for th e Red List of building materials)? *有害物質（特に添付のRed list に含まれるもの）が人体や環境に与える影響を緩和するための技術を使用していれば、差し支えない範囲で教えて下さい。*						
10. Moisture content (%) **含水率（%）**		*((wet weight – dry weight) / dry weight) x 100 %* *((湿潤重量 - 乾燥重量)/ 乾燥重量)×100 (%)*				
11. Fire-resistance rating FRR (minutes) **耐火性能（分）**		*FRR can be quantified as a measure of the period of time in respect to how long it would take fire to affect the material's structural abilities (for example ½, 1, 2, 4 hours).* *耐火性能は火災時に一定の構造的性能を維持できる時間で表されます（30分、1、2、4時間等…）。*				
12. Embodied carbon coefficient (kgCO2/kg) **CO2排出量**		*Embodied Carbon Coefficients (ECC) are expressed in kg of CO2e (kgCO2e) per kg of material (kgm), where CO2e stands for the equivalent in carbon dioxide of the greenhouse gases (GHG) produced for the manufacturing and transportation of the material.* *ECC は材料1 (kg) あたり、製造・運搬中に排出されるCO2(kg) です。*				
13. Solar reflectance (SR) **日射反射率**		*Materials with light colours have higher reflection factors than materials with dark colours (scale from 0 to 100)* *日射反射率は内装材・外装材使われる0~100 の間の数値で、明るい色の材料ほど高く、暗い色の材料ほど低い傾向があります。熱放射は含みません。*				
14. Solar Reflectance Index (SRI)		*SRI is a scale from 0 to 100 on which materials that absorb and retain solar radiation have a lower number, whilst highly reflective materials have a higher number.* *SRI は主に外装材を対象として建材の熱環境への影響を評価するのに使用される指標で、0~100 の値で表されます。熱放射を含みます。日射を吸収し蓄える材料は低い値になり、よく反射する材料は高い値になります。*				
15. Noise Reduction Coefficient (NRC) (for the innermost finishing materials) **騒音減少率**		*Sound absorption coefficient (∝) can assume values in a range from 0 (totally reflecting surfaces) to 1 (totally absorbing surfaces)* *音を完全に反射する場合は0、完全に吸収する場合は1になります。*				
16. Embodied energy intensity (MJ/kg) **エネルギー消費量 (MJ/kg)**		*Embodied energy is measured as the quantity of non-renewable energy per unit of building material, component or system* *Embodied energy はその材料の単位（重さ、部材ごと、もしくはシステムごと）ごとの回収できないエネルギー量です。*				
17. Thermal conductivity (W/m.K) **熱伝導率 (W/m.K)**		*Heat transfer occurs at a lower rate in materials of low thermal conductivity than in materials of high thermal conductivity.* *熱伝導率が低い材料では熱移動が起きにくく、高い材料では熱移動が起きやすくなります。*				
18. Specific Heat Capacity (J/kg.K) **比熱容量 (J/kg.K)**		*A good insulator material has a higher specific heat capacity because it takes time to absorb more heat before it actually heats up to transfer the heat* *比熱容量が高い材料は熱を伝えにくくなります。*				
19. Density (kg/m3) **密度 (kg/m3)**		*A high-density material maximizes the overall weight and is an aspect of low thermal diffusivity and high thermal mass* *密度が高いと重量が大きくなり、また低熱拡散率、高熱容量になる傾向があります。*				
20. Embodied Water Intensity (KL/Unit) **水の使用量 (KL/Unit)**		*Embodied water can be defined as the water needed to create and deliver a product or material through all stages of manufacturing.* *Embodied water は製品の製造・流通すべての段階を通して必要とされる水の量です。*				

II: The selection of building envelope assemblies

Development of a multi-criteria optimization approach for the selection of building envelope assemblies (walls and roofs)
建築外皮（壁・屋根）の建材選定における多基準最適化手法の開発

Building Type: Residential/ Office Buildings

1. Layers of the building Envelope **please specify from outermost layer to the innermost layer** **建築外皮の層** **＊最外層から最内層までご指定ください**			**Please choose one of the following options** ***＊当てはまる方を選んで下さい***		***Notes*** ***注釈***
The layers of building envelope **建物外皮の層**	**Name** **層の名前**	**Thickness (m)** **厚さ**			
Layer I			○ Structural構造用	○ Non-structural非構造用	
Layer II			○ Structural構造用	○ Non-structural非構造用	
Layer III			○ Structural構造用	○ Non-structural非構造用	
Layer IV			○ Structural構造用	○ Non-structural非構造用	
Layer V			○ Structural構造用	○ Non-structural非構造用	
Layer VI			○ Structural構造用	○ Non-structural非構造用	
Layer VII			○ Structural構造用	○ Non-structural非構造用	

2. Percentage recycled content (%) **リサイクル率（体積%）**	Pre-consumer % 廃棄物等を使用している割合	Post-consumer % 供用後にリサイクルできる	Total recycled content % 全体のリサイクル率	***Notes*** ***注釈***
3. The expected life time of the overall envelope (Years) **設計寿命（年）**				

4. Expected Maintenance and Replacement (Years) **想定する維持管理作業の周期（年）**	Need Maintenance /Repairing維持・修理 (for example every 5 years)	Need Replacement交換 (for example every 15 years)	***Notes*** ***注釈***
Layer I	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	
Layer II	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	
Layer III	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	
Layer IV	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	
Layer V	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	
Layer VI	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	
Layer VII	*修理・維持の時期・回数について教えてください。*	*交換時期・回数について教えてください。*	

5. Design for disassembly /deconstruction **分解性を考慮した設計**	Building envelope can be fully disassemble 完全に分解可能	Building envelope can be partially disassemble 一部分解可能	Design for disassembly is not considered 分解性は考慮されていない	Some layers can be reused 一部の層が再利用可能	Some layers can be recycled 一部の層がリサイクル可能	Building layers will be sent to landfill as waste at the end of their lifetime 各層は供用期間を終え、廃棄される	***Notes*** ***注釈***
*Please choose from the following options ＊当てはまる方を選んで下さい	☐	☐	☐	☐	☐	☐	
5.1 Is the envelope prefabricated? 外皮はプレハブか（現場作業の前に	○ Yes			○ No			

5.2 Please specifiy the connections types used to fix materials (layers) into the envelope? 各層の材料を外皮として組み立てる際の接着方法	Mechanical and dry connections are used (for example bolted and screwed connections) 機械的もしくは乾式の接着方法（ボルト・ねじ等）	Wet/chemical connections are used (for example adhesives and mortar) 化学的もしくは湿式の接着方法（接着剤・モルタル等）	Both mechanical and wet connections are used 機械的な接合と湿式の接着を併用	***Notes*** ***注釈***
* Please choose one of the following options ＊当てはまる方を選んで下さい	○	○	○	

6. End-of-life strategies (for each layer) **供用終了後の戦略** please select from the following options *当てはまるものに〇をつけて下さい	Reusable 再利用性	Renewacyclable 再利用・リサイクル可能な原料を用い、環境を汚染することなく廃棄できる。	Recyclable リサイクル性	Semi-reusable 半再利用性。物理的・科学的に変化は少ないがもとの性能を損なっており、元とは違う用途で使われる。	Semi-recyclable 半リサイクル性。リサイクルできるがもとの性能を損なっており、元と同じ用途で使われるとは限らない。	Non-recyclable or Non-renewable Material 再利用、リサイクルできない	***Notes*** ***注釈***
Layer I	○	○	○	○	○	○	
Layer II	○	○	○	○	○	○	
Layer III	○	○	○	○	○	○	
Layer IV	○	○	○	○	○	○	
Layer V	○	○	○	○	○	○	
Layer VI	○	○	○	○	○	○	
Layer VII	○	○	○	○	○	○	

7. Availability of materials and labours locally	Are any of the envelope layers produced locally? 外皮を構成する層の少なくともひとつは現地で生産・調達できるか		Are there available local labours to fix the envelope into building? 外皮を建築として組み立てるための労働力を現地で用意できるか		***Notes 注釈***
材料、労働力が現地で生産・調達できるか	○ Yes	○ No	○ Yes	○ No	
8. Life cycle cost (LCC) ライフサイクルコスト	Initial cost ($/m2) 生産コスト	Maintenance cost ($/m2) 修理・維持コスト	Replacement cost ($/m2) 交換コスト	Demolition cost ($/m2) 解体コスト	***Notes 注釈***
** US ドルに換算をお願いいたします。*					

9. Red List / Chemical avoidance list 有害な化学物質	Are there any specific chemical substances? 何らかの制限のある有害な化学物質を含有していますか？ *(please check the attached common hazardous list)* *(添付の有害物質リストをご確認ください)*		***Notes 注釈***
	○ Yes	○ No	
If yes, please specify the percentage 含有している場合、その割合		*The weight of the hazardous chemicals in a certain material can be explained as ppm (part per million) 有害物質の重量割合（%）（いくつかの有害物質では単位ppm）*	
Please specify the Current technology the company might developed to mitigate the impact on health and environment (especially for th e Red List of building materials)? 有害物質（特に添付のRed listに含まれるもの）が人体や環境に与える影響を緩和するための技術を使用していれば、差し支えない範囲で教えて下さい。			
10. Moisture content (%) 含水率（%）	*((wet weight – dry weight) / dry weight) x 100 % ((湿潤重量 - 乾燥重量)/ 乾燥重量)×100 (%)*		***Notes 注釈***
Layer I			
Layer II			
Layer III			
Layer IV			
Layer V			
Layer VI			
Layer VII			

10.1 Face seal and flashing details	○ Good	○ Poor	
10.2 Drained cavitiy/waterproofing layer is provided 排水用の穴や防水層が施されているか	○ Yes	○ No	
10.3 Air/Vapour barrier is installed 空気/蒸気が遮断されているか	○ Yes	○ No	
11. Fire-resistance rating FRR of the envelope (minutes) 耐火性能（分）		*FRR can be quantified as a measure of the period of time in respect to how long it would take fire to affect the material's structural abilities (for example ½, 1, 2, 4 hours). 耐火性能は火災時に一定の構造的性能を維持できる時間で表されます（30分、1、2、4時間等…）。*	
12. Embodied carbon coefficient for each layer (kgCO2/kg) CO2排出量	*Embodied Carbon Coefficients (ECC) are expressed in kg of CO2e (kgCO2e) per kg of material (kgm), where CO2e stands for the equivalent in carbon dioxide of the greenhouse gases (GHG) produced for the manufacturing and transportation of the material. ECC は材料1 (kg) あたり、製造・運搬中に排出されるCO2(kg) です。*		***Notes 注釈***
Layer I			
Layer II			
Layer III			
Layer IV			
Layer V			
Layer VI			
Layer VII			

13. Solar reflectance (SR) for the innermost layer 日射反射率		*Materials with light colours have higher reflection factors than materials with dark colours (scale from 0 to 100) 日射反射率は内装材・外装材使われる0~100 の間の数値で、明るい色の材料ほど高く、暗い色の材料ほど低い傾向があります。熱放射は含みません。*	
14. Solar Reflectance Index (SRI) for the outermost layer		*SRI is a scale from 0 to 100 on which materials that absorb and retain solar radiation have a lower number, whilst highly reflective materials have a higher number. SRI は主に外装材を対象として建材の熱環境への影響を評価するのに使用される指標で、0~100 の値で表されます。熱放射を含みます。日射を吸収し蓄える材料は低い値になり、よく反射する材料は高い値になります。*	
15. Sound Transmission loss (dB) of the envelope 音響透過損失		*The reduction in airborne noise of a roof or wall construction is referred to as the sound reduction index (R) also called sound transmission loss (STL) and it is a single number expressed in decibels (dB). 屋根や壁による騒音の低減は音響透過損失などと呼ばれ、単位(dB)で表されます。*	

16. Embodied energy (MJ/m2) **エネルギー消費量 (MJ/m2)**		*Embodied energy is measured as the quantity of non-renewable energy per unit of building material, component or system* *Embodied energy はその材料の単位（重さ、部材ごと、もしくはシステムごと）ごとの回収できないエネルギー量です。*		
17. Thermal transmittance (W/m2.K) **（外皮全体としての）熱貫流率**		*Thermal transmittance can be defined as the amount of heat energy that flows through a certain element per unit area and time, and it is measured in watts per square meter per kelvin (W/(m2.K)).* *熱貫流率はある材料を単位面積/単位時間あたりに通り抜ける熱エネルギーで、(W/m2K) の単位で表されます。*		
18. Thermophysical properties of the layers **各層の熱物性値**	**Thermal conductivity (W/m.K)熱伝導率 (W/m.K)**	**Specific Heat Capacity (J/kg.K)** **比熱容量 (J/kg.K)**	**Density (kg/m3)** **密度 (kg/m3)**	***Notes*** ***注釈***
Layer I				
Layer II				
Layer III				
Layer IV				
Layer V				
Layer VI				
Layer VII				
19. Windows properties **窓の性能**	**Visible Transmittance (VT)** *The Visible Transmittance (VT) is an optical property that specifies the amount of visible light transmitted through the windows (a higher value allows more light to be transmitted and is desirable to maximize daylight).* *可視光透過率*	**Solar Heat Gain Coefficient (SHGC)** *The solar heat gain coefficient (SHGC) is the ratio of the solar heat gain that is transmitted through the window area to the incident solar radiation (including window frames). The SHGC is expressed as a number from 0 to 1.* **太陽熱利得係数**	**Thermal transmittance of windows U-factor (W/m2.K)** *Thermal transmittance is quantifying the rate of loss of non-solar heat of a window assembly and can be expressed as U-factor.* **窓の熱貫流率（U値）**	***Notes*** ***注釈***

20. Embodied Water Intensity (KL/Unit)	**Embodied Water Intensity (KL/Unit)** **Embodied water can be defined as the water needed to create and deliver a product or material through all stages of manufacturing.** **Embodied waterは製品の製造・流通すべての段階を通して必要とされる水の量です。**	***Notes*** ***注釈***
Layer I		
Layer II		
Layer III		
Layer IV		
Layer V		
Layer VI		
Layer VII		

Appendix F: Thermophysical properties of some building materials

Material	thermal conductivity λ [W/m.K]	gross density ρ [kg/m^3]	spec. heat capacity C [J/kg.K]
Aerated concrete	0.100	300	1370
Aerated concrete	0.140	500	1290
Aerated concrete	0.270	900	1180
AGEPAN THD Static 40/60/80 mm	0.050	230	2100
AGEPAN THD Static	0.050	230	2100
Agepan DWD protect	0.090	565	2100
AGEPAN OSB 3 PUR EN 300	0.130	600	2100
AGEPAN OSB 4 PUR EN 300	0.130	600	2100
AGEPAN UDP N+F 22/25/32 mm	0.063	270	2100
Aluminium	237.000	2700	888
Aluminium alloy	160.000	2800	880
Anhydrite screed	0.700	2200	1300
Asphalt	0.700	2100	1000
Bitumen felt/sheet	0.230	1100	1000
Bitumen pure	0.170	1050	1000
Brass	120.000	8400	380
Brick 1500 kg/m^3	0.400	1500	850
Brick 700 kg/m^3	0.170	700	850
Brickwork	0.320	1300	840
Brickwork	0.500	1700	830
Brickwork	0.730	2200	820
Brick-work	0.160	800	920
Butadiene	0.250	980	1000
Butyl, (isobutene), solid/hot melt	0.240	1200	1400
Carpet, textile floor	0.060	200	1300
Cement lime plaster	0.700	1600	1100
Cement mortar	1.400	2000	800
Cement screed	1.330	2000	1080
Cement, sand	1.000	1800	1000
Cement-bonded particleboard	0.230	1200	1500
Cement-lime mortar	0.800	1800	1100
Chipboard (wood)	0.081	300	2500
Chipboard (wood)	0.100	500	2500
Chipboard (wood)	0.140	800	2500
Clay/Silt	1.500	2000	1500
Clinker brick (holes<=15%); std.mortar	0.800	1900	1000
Clinker brick (holes>15%); std.mortar	0.730	1700	1000
Coloured Rendering Mortar	0.780	1600	1000
Concrete (crushed stone aggregates)	0.980	1600	1080
Concrete (crushed stone aggregates)	1.710	2300	1080
Concrete (EPS aggregates)	0.190	450	1320

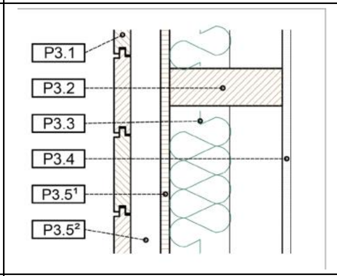
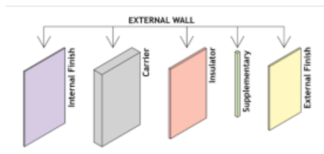
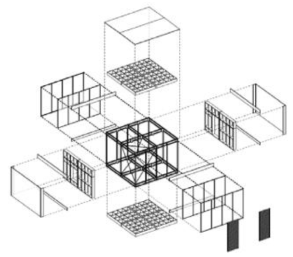
Material	thermal conductivity λ [W/m.K]	gross density ρ [kg/m³]	spec. heat capacity C [J/kg.K]
Concrete (EPS aggregates)	0.250	600	1240
Concrete (EPS aggregates)	0.350	850	1180
Concrete (expanded shale aggregates)	0.430	1100	1140
Concrete (expanded shale aggregates)	0.670	1700	1090
Concrete (light gravel aggregates)	0.240	1100	1140
Concrete (light gravel aggregates)	0.390	1200	1060
Concrete (light gravel aggregates)	0.400	1400	1110
Concrete (light gravel aggregates)	0.890	1800	1040
Concrete 1800kg/m³	1.150	1800	1000
Concrete 2000kg/m³	1.350	2000	1000
Concrete 2200kg/m³	1.650	2200	1000
Concrete 2400kg/m³	2.000	2400	1000
Concrete hollow brickwork	0.440	800	1190
Concrete hollow brickwork	0.620	1400	1110
Concrete hollow stone (unfilled)	0.600	800	1190
Concrete hollow stone (unfilled)	1.200	1400	1110
Concrete reinforced	2.300	2300	1000
Concrete reinforced 1%	2.300	2300	1000
Concrete reinforced 2%	2.500	2500	1000
Copper	380.000	8900	380
CrNi-Steel (X12CrNi18,8)	15.000	7800	500
EPDM (Ethylenpropylendien, monomer)	0.250	1500	1000
EPS 030	0.030	20	1450
EPS 035	0.035	20	1450
EPS 041	0.041	20	1450
EPS W15	0.041	15	1450
EPS W20	0.038	20	1450
EPS W25	0.036	25	1450
EPS W30	0.035	30	1450
EPS-F	0.040	17	1450
Expanded clay mortar	0.400	1000	1150
Ext. rendering	0.870	1800	1100
Fibreboard, MDF (250 kg/m³)	0.070	250	1700
Fibreboard, MDF (400 kg/m³)	0.100	400	1700
Fibreboard, MDF (600 kg/m³)	0.140	600	1700
Fibreboard, MDF (800 kg/m³)	0.180	800	1700
Foam glass	0.041	100	1000
Foam glass	0.059	180	1000
General Purpose Plaster	0.490	1300	1000
General Purpose Plaster	0.780	1600	1000
General Purpose Plaster	1.050	1800	1000
Glass (quartz glass)	1.380	2200	1050
Glass wool	0.032	35	1030

Material	thermal conductivity λ [W/m.K]	gross density ρ [kg/m³]	spec. heat capacity C [J/kg.K]
Glass wool	0.035	50	1030
Gold	316.000	19260	129
Gypsum (1200)	0.430	1200	1000
Gypsum (1500)	0.560	1500	1000
Gypsum (600)	0.180	600	1000
Gypsum (900)	0.300	900	1000
Gypsum fibre board	0.400	1125	1000
Gypsum insulating plaster	0.180	600	1000
Gypsum light plaster	0.180	600	1000
Gypsum plaster board	0.210	900	960
Gypsum plasterboard	0.250	900	1000
Gypsum wall board	0.190	600	1000
Gypsum wall board	0.370	1000	1000
Gypsum wall board	0.550	1400	1000
Gypsum, sand	0.800	1600	1000
Hollow brick <17cm; Std. mortar	0.280	650	1000
Hollow brick <17cm; thin-bed mortar/PUR	0.420	1000	1000
Hollow brick >30cm; Light mortar	0.089	575	1000
Hollow brick >30cm; thin-bed mortar/PUR	0.130	825	1000
Hollow brick 17-38 cm; Light mortar	0.230	675	1000
Hollow brick 17-38 cm; Light mortar	0.320	975	1000
Hollow brick 17-38 cm; Std. mortar	0.240	675	1000
Hollow brick 17-38 cm; Std. mortar	0.577	1450	1000
Hollow brick 17-38 cm; thin-bed mortar/PUR	0.220	675	1000
Hollow brick 17-38 cm; thin-bed mortar/PUR	0.350	1150	1000
Hollow brick concrete filled <=30cm; thin-bed mortar/PUR	0.640	1640	1000
Hollow brick concrete filled <=30cm; thin-bed mortar/PUR	0.829	1810	1000
Hollow brick old (until 1980); Std. mortar	0.450	1000	1000
Hollow brick stone-wool filled <=30cm; thin-bed mortar/PUR	0.090	750	1000
Hollow brickwork	0.420	800	880
Hollow brickwork	0.580	1400	850
Ice at -10°C	2.300	920	2000
Insulation (XPS)	0.039	35	1450
Insulation cork (DK-P)	0.050	140	1670
Iron, cast	50.000	7500	450
Isover Akustic EP 3	0.040	150	1000
Isover Clima 34	0.034	70	1000
Isover TP 1	0.039	12	840
Isover Uniroll Classic	0.038	14	1030
Lead	35.000	11300	130
Light mortar	0.370	900	1170

Material	thermal conductivity λ [W/m.K]	gross density ρ [kg/m³]	spec. heat capacity C [J/kg.K]
Light mortar	0.520	1200	1130
Light mortar	0.800	1500	1100
Lightweight concrete (expanded clay aggregates)	0.140	450	1320
Lightweight concrete (expanded clay aggregates)	0.310	900	1170
Lightweight concrete (expanded clay aggregates)	0.550	1400	1110
Lightweight Plaster	0.120	350	1000
Lightweight Plaster	0.590	1300	1000
Lime, sand	0.800	1600	1000
Lime-cement mortar (for masonry)	1.050	1800	1000
Limestone, hard	1.700	2200	1000
Linoleum	0.170	1200	1400
Marble	3.500	2800	1000
Masonry brick <25% holes; std.mortar	0.480	1100	1000
Masonry brick <25% holes; std.mortar	0.590	1400	1000
Molybdenum	138.000	10200	251
Mortar	0.930	950	800
Natural stone porous, e.g. lava	0.550	1600	1000
Natural stone, crystalline rock	3.500	2800	1000
Natural stone, sedimentary rock	2.300	2600	1000
One Coat Mortar	0.490	1300	1000
One Coat Mortar	1.050	1800	1000
OSB Board	0.130	600	1700
Particleboard (300 kg/m³)	0.100	300	1700
Particleboard (600 kg/m³)	0.140	600	1700
Particleboard (900 kg/m³)	0.180	900	1700
Perlite (loose)	0.060	100	900
Perlite board	0.060	180	900
Perlite insulation mortar	0.190	600	1240
Perlite insulation plaster	0.230	700	1210
Plaster	0.700	1400	1000
Plastic	0.250	1700	1400
Plywood (1000 kg/m³)	0.240	1000	1600
Plywood (300 kg/m³)	0.090	300	1600
Plywood (700 kg/m³)	0.170	700	1600
Polyacetate	0.300	1410	1400
Polyamide 6.6 with 25 % glass fibre	0.300	1450	1600
Polycarbonates	0.200	1200	1200
Polyester resin	0.190	1400	1200
Polyurethane (PU)	0.250	1200	1800
Polyurethane (PU) foam	0.050	70	1500
Polyvinylchloride (PVC)	0.170	1390	900
Polyvinylchloride (PVC) flexible, with 40 % softener	0.140	1200	1000

Material	thermal conductivity λ [W/m.K]	gross density ρ [kg/m³]	spec. heat capacity C [J/kg.K]
PU (Polyurethane)	0.250	1200	1800
PVC (polyvinyl chloride)	0.170	1390	960
Quartz glass	1.400	2200	750
Reinforced concrete (1%)	2.300	2300	1000
Reinforced concrete (2%)	2.500	2400	1000
Rock wool	0.034	60	1030
Rock wool	0.040	160	1030
Roof tile (clay)	1.000	2000	800
Roof tile (concrete)	1.500	2100	1000
Rubber	0.170	1200	1400
Sand/Gravel	2.000	2000	1000
Sandstone (silica)	2.300	2600	1000
Silica gel (dessicant)	0.130	720	1000
Silicone foam	0.120	750	1000
Silicone, filled	0.500	1450	1000
Silicone, pure	0.350	1200	1000
Snow freshly fallen <30mm	0.050	100	2000
Snow, compacted (<200mm)	0.600	500	2000
Soda lime glass (float glass)	1.000	2500	750
Stainless steel	17.000	7900	460
Steel	50.000	7800	450
Tiles, clay	1.000	2000	800
Tiles, concrete	1.500	2100	1000
Tiles, cork	0.065	400	1500
Timber (500 kg/m³)	0.130	500	1600
Timber (700 kg/m³)	0.180	700	1600
Underlay, cellular	0.100	270	1400
Underlay, felt	0.050	120	1300
Underlay, wool	0.060	200	1300
Water at 10°C	0.600	1000	4190
Wood 500 kg/m³	0.130	500	1600
Wood 700 kg/m³	0.180	700	1600
Wood fibre insulation board	0.045	150	2500
Wood fibre insulation board	0.060	300	2500
Wood wool layer 10mm (WW)	0.100	600	1470
Wood wool layer 7mm (WW)	0.125	600	1470
XPS 029	0.029	35	1450
XPS 031	0.031	35	1450
XPS 033	0.033	35	1450
XPS 035	0.035	35	1450
XPS 037	0.037	35	1450
XPS 039	0.039	35	1450
Zinc	121.000	7100	387

Appendix G: Common aspects of design for disassembly (materials and connections)

	DfD - common aspects of connections	Strategies/methods	Illustrations
1	The start point for disassembly is identified?	Disassembly sequence diagram, Integrated set of “as-built” drawings for maintenance and deconstruction purposes	
2	Bolted and screwed connections are used rather than chemical connections (avoid the use of binders, adhesive and resin)?	Screws, pins, nuts and bolts	
3	The joints/connections between assemblies’ layers are visible and accessible?	Mechanical joining	
4	Access to subassemblies has been considered; particularly those which need to be maintained, repaired, or modified regularly (decoupling of independent layers that have different degrees of durability?	Layer-by-layer assembly (LbL), Integrated set of “as-built” drawings for maintenance and deconstruction purposes	
5	Building assembly (infill materials) is separated from the structure?	Building parts must be kept independent from one another by creating dependent relations only with one element within an assembly (reversible assembly)	
6	Building assembly is separated from mechanical, electrical and plumbing systems?	Enable the disassembly of the components and materials for repair, replacement, reuse and recycling	
7	Human-scale and standardized materials are applied?	Components are sized to suit handling	

Appendix H: The layers, chemical substances, classification, and concentration weight of sub-substances of a typical drylined hollow block construction

Assembly layers (from outside to inside)	General Description	Substances		Sub-substances		Weight%	Function	Known hazardous	Score
Concrete Masonry Unit (CMUs)	Hollow concrete masonry units (CMUs), commonly referred to as “cinder blocks,” are made from hydraulic cement, water, and aggregates.	1	Aggregate	Gravel		53.69	solvent	-	10
				Pumice		35.97		-	
		2	Portland cement	Clinker	TRICALCIUM SILICATE	6.41	binder	-	
					DICALCIUM SILICATE	1.10		-	
					ALUMINIUM CALCIUM IRON OXIDE	0.82		-	
					CALCIUM ALUMINATE	0.64		-	
					MAGNESIUM OXIDE	0.37		-	
					CALCIUM OXIDE	0.18		-	
				Flue Gas Desulfurization (FGD) Gypsum		0.5	retarding admixture	-	
		3	Additives	TRIETHANOLAMINE		<0.01	water reducer	-	
				CALCIUM STEARATE		<0.01	waterproofing	-	
Steel Studs	Drywall studs are used as the vertical support in wall framing and are typically made of galvanized steel.	1	Steel (ASTM A1003)	IRON		94.01	base metal	-	6
				MANGANESE		1.11	alloying element	-	
				CARBON		0.24	alloying element	-	
				NICKEL		0.19	alloying element	-	
				COPPER		0.19	alloying element	-	
				PHOSPHORUS		0.19	alloying element	-	
				CHROMIUM		0.18	alloying element	-	
				MOLYBDENUM		0.07	alloying element	-	
				SULFUR		0.04	alloying element	-	
				VANADIUM		0.02	alloying element	-	
				TITANIUM		0.02	alloying element	-	
				NIOBIUM		0.02	alloying element	-	
		2	Hot Dipped Galvanized Coating	ZINC		3.71	metallic coating	-	
				Aluminium Powder (pyrophoric)		0.01	metallic coating	√	
Mineral Wool Board Insulation	Mineral fibres are manufactured by spinning a molten mixture of rock wool (derived from igneous rocks such as basalt) and slag wool (derived from blast furnace slag from the steel industry) into fine fibres. An atomized binder (commonly urea)	1	Mineral wool, biosoluble and/or with alkaline oxide and alkali earth oxide content ≤ 18% by weight	-		97.94	Fibre base	-	0
		2	Urea phenol formaldehyde	-		2.06	Binder	√	
Vapour barrier	An under-slab vapour barrier/retarder is employed to reduce the water vapour transmission through a concrete slab into the building envelope.	1	Polyethylene Film Flu	POLYETHYLENE		98.29	Vapour barrier	-	10

Assembly layers (from outside to inside)	General Description	Substances		Sub-substances		Weight%	Function	Known hazardous	Score
Drywall (FGD)	Drywall is ubiquitously used in building construction as interior wall enclosures, ceilings, and partitions in both load-bearing and non-load-bearing cases	1	FGD Drywall Core	Flue Gas Desulfurization (FGD) gypsum		88.53	Structure Comp-	-	4
				WATER		2.57	Moisture	-	
				STARCH		1.31	Binder	-	
				Residuals in Processed Drywall Gypsum (FGD)	QUARTZ	0.24	Impurity	-	
					POTASSIUM	0.02	Impurity	-	
					Sodium metal	0.02	Impurity	-	
					Manganese	<0.01	Impurity	-	
					ZINC	<0.01	Impurity	-	
					Nickel	<0.01	Impurity	-	
					Chromium	<0.01	Impurity	-	
					LEAD	<0.01	Impurity	√	
					VANADIUM	<0.01	Impurity	-	
					SELENIUM	<0.01	Impurity	-	
					ARSENIC	<0.01	Impurity	√	
					COBALT	<0.01	Impurity	-	
					MERCURY	<0.01	Impurity	√	
					THORIUM	<0.01	Impurity	-	
					URANIUM, SOLUBLE SALTS	<0.01	Impurity	-	
					ZIRCONIUM	<0.01	Impurity	-	
					ANTIMONY	<0.01	Impurity	-	
					BERYLLIUM	<0.01	Impurity	-	
					CADMIUM	<0.01	Impurity	√	
				2-Naphthalenesulfonic acid, polymer with formaldehyde, sodium salt		0.25	Dispersant	-	
				BORIC ACID		0.15	Strengthener	-	
				GLUCOSE		0.08	Humectant	-	
				Poly(oxy-1,2-ethanediyl), alpha-sulfo-omega-hydroxy-, C8-10-alkyl ethers, ammonium salts		0.06	Foaming Agent	-	
				Protein hydrolysate [USP]		0.02	Retarder	-	
				SODIUM SULFATE		0.03	Accelerator	-	
		2	Drywall Paper Facing	Cellulose, microcrystalline		5.65	Cellulose Fiber	-	
				STARCH		0.31	Binder	-	
				LIMESTONE, CALCIUM CARBONATE		0.29	Filler	-	
				Kaolin, calcined		0.21	Filler	-	
				Bentonite		0.02	Filler, Retention Agent	-	
		3	ETHYLENE VINYL ACETATE POLYMER (EVA)	-		0.24	Adhesive	-	

Appendix J: Tokyo climate data (obtained from climate consultant 6.0)

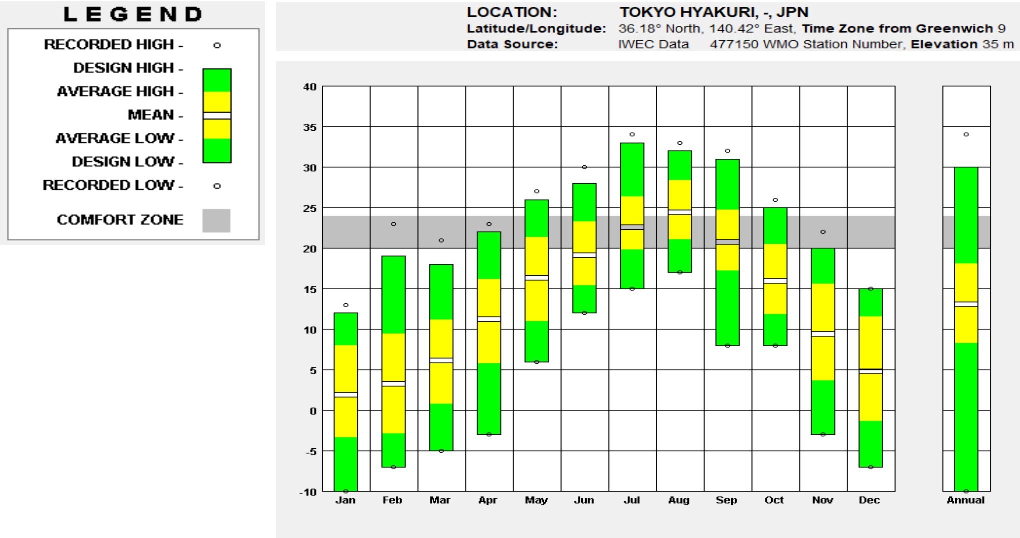


Figure J-1: Temperature range and comfort zone

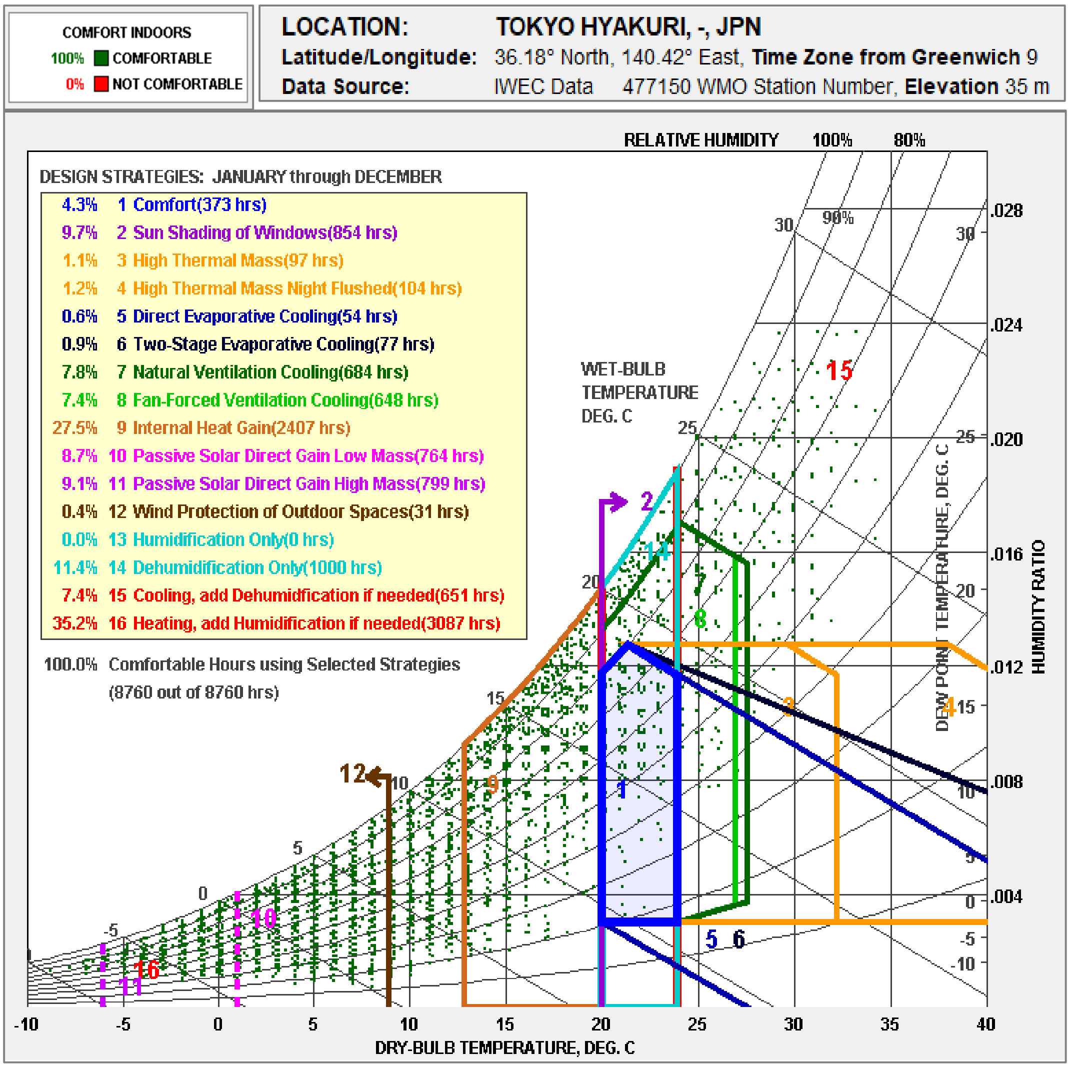


Figure J-2: Psychometric chart, the subtle attributes of climate, and its impact on built form

CURRICULUM VITAE

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Mohamed **O**mer was born in Sennar (A town on the Blue Nile in Sudan). He started his primary education in Al-Gadarif (State in the Eastern part of Sudan) where he joined Ismail Khaleel Primary School in 1993. In 2003, he completed his high school education at ALgadarif High Secondary School. Six years later, in 2009, he obtained his undergraduate degree from the Department of Architecture, University of Khartoum, Sudan with first-class honour. As of his academic excellence, he was appointed as a teacher assistant in the department of architecture University of Khartoum in 2009, where he worked as a teaching assistant for two years until 2011. His job involved guiding students in architectural design studio projects and follow-up lectures besides teaching students different architectural visualization programs.

Simultaneously, he worked as an architect and he joined the University of Khartoum consultancy corporation and many other private engineering consultancy companies. He handled different design projects, preparing architectural drawings sets and presentations for clients. Also, working in teams with architects, civil engineers and services engineers.

In 2011, he got a scholarship from the Sudan government (Developing Solution Scholarship for Master's Students) to start his master degree at the Department of Architecture and Built-Environment, The University of Nottingham, United Kingdom. He received his master degree with distinction in December 2012 in the field of Renewable energy and Architecture.

After finishing his master degree, he returned to Sudan to work as a lecturer at the Faculty of Architecture-University of Khartoum. He handled different academic and administrative jobs including handling the construction system module, working in examination committees, and working as a head department for the Self-Evaluation and Quality Control Unit. Besides working in many private and local universities in Sudan.

In July 2017, he obtained an honourable scholarship from the Government of Japan (MONBUKAGAKUSHO: MEXT) to commence his PhD research at the Building material Engineering Laboratory, Department of Architecture, University of Tokyo, Japan. He succeeded to complete the degree, and the document you are reading now is the final report of his Doctoral thesis.