BUILDING MATERIAL SELECTION FRAMEWORK FOR TROPICAL CLIMATIC CONDITIONS: AN ECO-DESIGN BASED APPROACH

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Degree of Master of Science

Department of Civil Engineering

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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

All over the world, sustainability has been given immense attention, thus novel state-of-the-art materials and building systems are emerging as alternatives. With those different alternatives, comparison and the selection of a better-performing material or a building system using diverse perspectives such as economic, ecological, social, and cultural are important to ensure the adaptation of the proposed research findings to the particular community. Even though many researchers introduced multiple material selection frameworks using economic and ecological parameters, a holistic approach including Social and Cultural adaptability of those selections has been overlooked in previous studies.

This study proposed an eco-design-based material selection approach that considers the individual and wholistic perspective of diverse themes including economic, ecological, social, and cultural. Several sub-themes are identified under each theme and are verified through expert surveys. The pairwise comparison of themes and sub-themes and analysis using the Analytical Hierarchy Process (AHP) leads to proposing weights for each theme and sub-theme and developing an eco-design-based material selection framework in ranking and choosing better-performing building materials. Accordingly, saving energy, reducing the overexploitation of natural resources, reducing energy emissions, and reducing construction, as well as operational cost, are the parameters that create a greater impact on the selection of sustainable material with the aid of eco-design.

Furthermore, the developed framework is validated by comparing an emerging walling material Cement Stabilized Earth Blocks (CSEB) with conventional materials such as Burnt Clay Bricks (BCB) and Cement Sand Blocks (CSB). Technique for Order Preference by Similarities to Ideal Solution (TOPSIS) had been carried out to compare and rank the respective walling materials under different scenarios. Accordingly, CSEB is concluded to be the best alternative when analyzed in the eco-design concept. Furthermore, individual analysis of ecological and economic themes shows that CSEB is the best material over the long run while BCB is said to be performing well socially and culturally.

The proposed framework could be highly beneficial for industry practitioners such as contractors, building developers, planners, and policymakers in choosing community-preferred, affordable, and environmental-friendly construction materials. Moreover, this piece of research could be improved with the inclusion of fuzzy numbers which enables consideration of uncertainty.

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LIST OF ABBREVIATIONS

SDG – Sustainable Development Goals

AP – Accredited Professionals

GBCSL – Green Building Council of Sri Lanka

IGBC – Indian Green Building Council

BREEAM - Building Research Establishment Environmental Assessment Method

LEED - Leadership in Energy and Environmental Design

RI – Relative Index

MCDM – Multi-Criteria Decision Making

AHP – Analytical Hierarchy Process

TOPSIS - Technique for Order Preference by Similarities to Ideal Solution

BCB – Burnt Clay Bricks

CSB – Cement Sand Blocks

CSEB - Cement Stabilized Earth Blocks

1. INTRODUCTION

1.1 Background

Climate change and resource scarcity has become key public issues in the world (Brunner, 1991). This is mainly due to anthropogenic Greenhouse Gas (GHG) emissions and the overexploitation of natural resources (Mann et al., 1998) (Lucas et al., 2015). Buildings can be considered one of the key energy users, which use around 40% of energy, 25% of water, and 40% of other resources globally, while also accounting for approximately 33% of GHG emissions (Mudiyanselage & Widvanga, 2018; Stocker et al., 2013; United Nations Environment Program, 2009). Building materials contribute significantly to the consumption of energy in the building and the GHG emissions over the lifespan of the building (Hong et al., 2015; Hossaini et al., 2014; Omer & Noguchi, 2020; Reza et al., 2011; Sagheb et al., 2011; Yüksek, 2015). Also, greater than 40% of the applied materials are non-renewable (Asif et al., 2007; Omer & Noguchi, 2020; Yahya & Boussabaine, 2010).

The decline of natural resources has become a serious issue and in order to minimize the issues with conventional materials, several newer materials are emerging and being implemented into practice as alternative materials (Bundgaard et al., 2017). As a result, the selection of sustainable and best desirable building materials and systems has become a complex task (Zhang et al., 2019). With the consideration of several aspects contributing together, and since the material selection has become complicated a multi-criteria-based decision-making approach has become a need (Reza et al., 2011).

Sustainability and life cycle thinking are appreciated worldwide and implemented in construction practices in the recent past (O. P. Akadiri, 2011). Meeting current requirements without sacrificing the ability of future generations to satisfy their own needs is what is meant by sustainability (Hossaini et al., 2014; Peuportier et al., 2013; Troyer, 1990). Life cycle thinking incorporates all the stages of a product or service from cradle to grave (Lu et al., 2017). Sustainable buildings, materials, and practices show better resilience, competitive costs, lower GHG emissions, lower energy, and non-renewable resource use compared to conventional and traditional materials and building systems(O. P. Akadiri, 2011). Literature reveals that eco-efficiency, life cycle assessment, and life cycle sustainability analysis were largely used by different researchers to assess sustainable materials and compare them with traditional materials (Gurupatham et al., 2021; Wen et al., 2020). Eco-design is a novel and more comprehensive technique to evaluate materials and building systems that cover a multi-faceted perspective of a specific product in a given context (Rio et al., 2013). Accordingly, the eco-design is several steps ahead of the conventional eco-efficiency that integrates sustainable aspects such as environmental, economic, social (triple-bottom-line), and cultural aspects (Lambrechts et al., 2019; Peuportier et al., 2013).

Since the majority of buildings in tropical climates and underdeveloped nations like Sri Lanka are constructed without an adequate internal cooling system, the building envelope and the material selection significantly contribute to improving the thermal comfort inside the structure. Every building material has unique characteristics (Wijnants et al., 2019). Therefore, picking the right enclosing materials is crucial. Although the sustainability of materials and building systems for tropical climatic conditions will largely be discussed in the literature, there is very limited literature available on selecting the best desirable materials and building systems for local buildings considering multiple perspectives and dimensions of those materials and the project location. The key aim of this study is to introduce a scientific material selection approach that explores various themes under the eco-design concept with the aid of local expert surveys and interviews.

1.2 **Objective**

The main objective of this study is to develop a decision-support framework to select building materials with the aid of the Eco-design concept. The study focuses on the following specific sub-objectives:

- To explore ecological, economic, social, and cultural parameters, which would affect the performance of building materials

- To develop an eco-design-based decision support framework to achieve optimal building materials for residential buildings considering tropical climatic conditions

1.3 Methodology

In order to achieve the above objectives, the following methodology was adopted.

- A comprehensive literature review was carried out in which the research gap was identified.
- The concept of eco-design and parameters associated with the selection of building materials were explored to identify the possible themes and sub-themes associated.
- The survey on the level of importance of parameters affecting material selection was prepared and carried out in the form of interviews in which the sub-themes were finalized.
- A survey on pairwise comparison of the themes and sub-themes was carried out among the experts in order to propose weights.
- A material selection framework was developed to achieve eco-design buildings for tropical climatic conditions.
- The developed framework was applied to a case study and the framework was validated.
- Best practice guidelines were developed for industry practitioners to achieve eco-design buildings in the long run.

The methodology has been interpreted in Figure 1.

1.4 Arrangement of the Thesis

- Chapter 1 introduces the research and identifies the research problem
- Chapter 2 summarizes the existing literature that was used to select building materials and summarizes the life cycle thinking-based decision-supporting methods and Multi-Criteria Decision-Making Approaches.

- Chapter 3 elaborates design and approach of the surveys carried out in order to collect data for the material selection framework
- Chapter 4 analyses the results of the survey responses
- Chapter 5 presents conclusions and recommendations with important findings and research contributions of the study

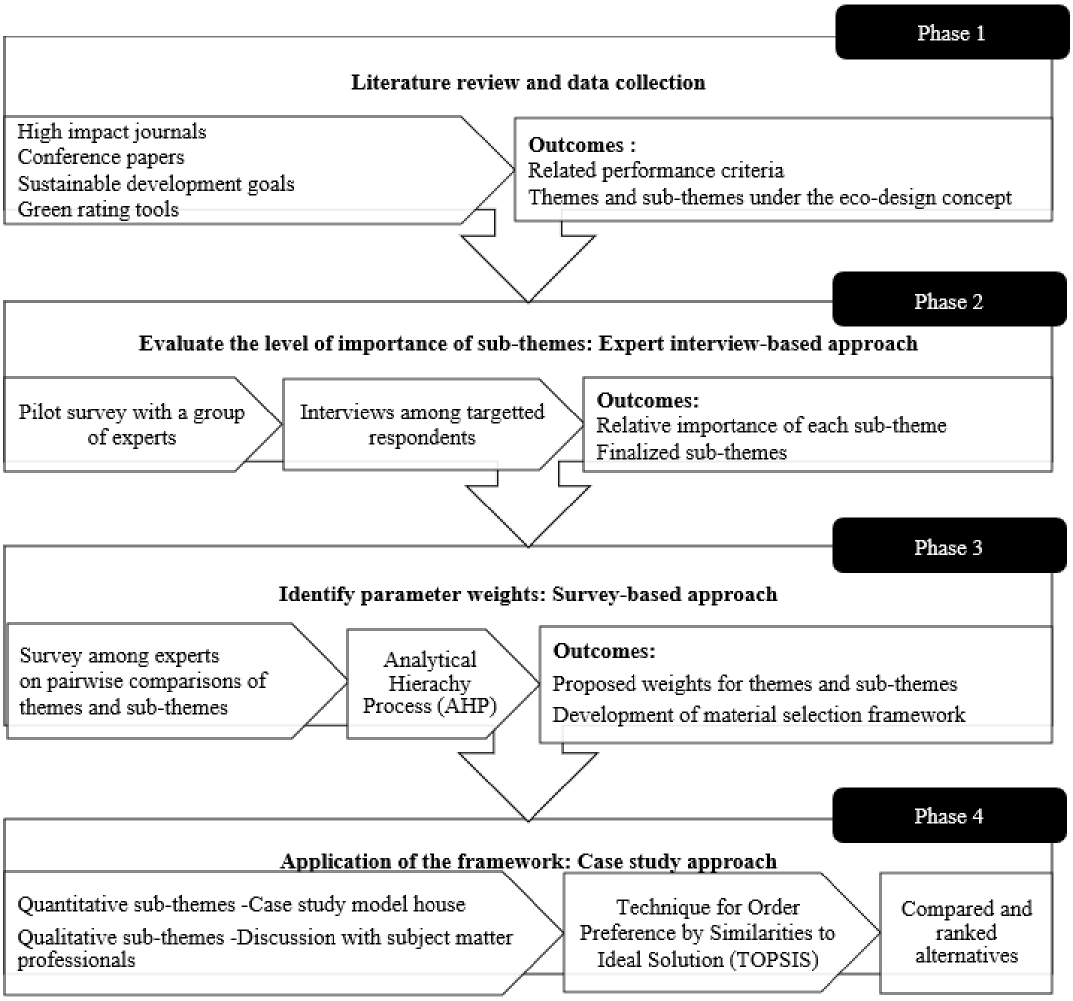

Figure 1: Methodology Framework

2. LITERATURE REVIEW

2.1 Introduction

The construction industry remarkably influences the aspects of sustainability in both developed and developing countries (Heravi & Abdolvand, 2019). It is contributing to around 40% of global energy consumption and around 40–50% of greenhouse gas emissions (Aneesh et al., 2018; Heravi & Abdolvand, 2019). The construction industry plays a significant role in consuming natural resources such as raw materials, energy, and water (Heravi et al., 2017; Heravi & Abdolvand, 2019). Environmental risks and increased costs result from using natural resources that are depleted over time (Thevarajah et al., 2020). Hence, the scarcity of natural resources is becoming a serious issue that results in high costs of construction (Thevarajah et al., 2020). Furthermore, the construction of households and their operation-related costs create a significant impact on local and global economic development (Kulshreshtha et al., 2020).

Natural or synthetic material that is being used for any construction is said to be a building material (Kubba, 2012a; Omer & Noguchi, 2020). A vast percentage of over 40% of the material application are non-renewable (Asif et al., 2007; Omer & Noguchi, 2020; Yahya & Boussabaine, 2010). Building materials contribute about 10% to 20% of the total building energy which will even increase with the development of the production of materials (Omer & Noguchi, 2020; Thillai Ramesh et al., 2014; Ruuska & Häkkinen, 2014). During the lifetime of the building, the materials play a major role in energy consumption and are contributing significantly to GHG emissions (Hong et al., 2015; Hossaini et al., 2014; Omer & Noguchi, 2020; Reza et al., 2011; Sagheb et al., 2011; Yüksek, 2015). Energy exists in the form of embodied as well as operational energies. Embodied energy as well as the operational energy of a building contributes to the GHG emission (T Ramesh et al., 2010; Thormark, 2006).

The decline of natural resources is becoming a trend in the aspect of environmental concerns (Bundgaard et al., 2017). Due to greater energy consumption and over-exploitation of natural resources, several newer materials are emerging as alternatives (C. Jayasinghe et al., 2016; C. Jayasinghe & Kamaladasa, 2007; Chintha Jayasinghe, 2011; Kariyawasam & Jayasinghe, 2016; Kota & Kalyana Rama, 2020). With the higher number of alternatives, building material selection has become a critical and complex task (Zhang et al., 2019). The selection of the most desirable materials for a specific building will not be straightforward, which might need a multi-criteria-based decision-making framework that satisfies sustainable practices (Reza et al., 2011).

Building material selection is playing an important role in the construction industry in paving way for sustainable development (Kubba, 2012b, 2012a; Milagre Martins & Gonçalves, 2012; Omer & Noguchi, 2020). Sustainable building materials are introduced such that they consume lower energy in construction as well as in the operational stages (Kariyawasam & Jayasinghe, 2016). Recent researches state that up to 30% of total emissions during a building lifetime could be reduced by careful selection of alternative materials (Chen & Thomas Ng, 2016; Wheating, 2017). Material selection becomes important to reduce negative impacts on the climate as well as human health by providing a better indoor environment (Pedersen Zari, 2019). The selection of these alternative materials and the use of the most desirable materials for building construction is significant in achieving sustainability. Improper selection of building materials could cause problems in terms of economy, functionality, and appearance that can even lead to a state in which it cannot be rectified easily (Alibaba & Özdeniz, 2004).

According to Ashby et al. (2004), the three primary strategies for material selection include a free searching strategy based on quantitative analysis, an expert questionnaire strategy, and inductive reasoning and analogy strategy (Ashby et al., 2004). Most of the studies have focused on quantitative performances and hence, qualitative aesthetic preferences of the end-user have been neglected. There is a lack of research on the investigation of the personal preferences of the end-users concerning material evaluation and selection (Zhang et al., 2019). The literature review reveals that there is a lack of knowledge on a standard method or proper material selection guidelines developed for tropical climatic conditions.

2.2 Factors affecting building material selection

The most desirable materials are selected by carrying out a preliminary comparative study based on multiple criteria. Expert opinions conclude that the parameters for building material selection need to be comprehensive, transparent, and practical (O. P. Akadiri, 2011; Sahlol et al., 2021).

Strength is one of the major areas that need to be focused on while selecting a material for any element (Kariyawasam & Jayasinghe, 2016). On the other hand, there are other structural parameters as well as performance criteria that are taken into consideration while selecting the most suitable material. Durability and thermal performance are predominant factors when the building performance is considered (Chintha Jayasinghe et al., 2016). Both mass materials and high carbon-emitting materials need to be given special attention while selecting building materials (Kumanayake et al., 2018) in order to lead to sustainable development.

In addition to structural parameters and durability aspects, the factors influencing the material selection could be categorized as economic, ecological, social, and cultural aspects that lead to a better selection of sustainable building materials. Peuportier et al. (2013) have listed various goals and objectives under each of the above aspects under the concept of eco-design that paves way for sustainability (Peuportier et al., 2013). Sahlol et al., (2021) identified various parameters and categorized them under environmental, socioeconomic, and technical categories in selecting sustainable materials (Sahlol et al., 2021). A summary of sustainability considerations related to the construction industry extracted from the literature has been provided in Table 1 (Abeysundra et al., 2007; P. O. Akadiri et al., 2013a; Hossaini et al., 2014; Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004; Zuo & Zhao, 2014). Accordingly, saving energy, reducing waste, or proper disposal of waste which includes recycling and reuse, reducing the usage of toxic materials or materials with hazardous content, reducing life cycle costs, health and safety of occupants, improving thermal comfort and use of local regional materials are the highly repeated parameters. Consideration of several qualitative, as well as quantitative parameters in selecting desirable materials, would lead to sustainable buildings.

Table 1: Sustainability issues related to construction

Dimensions	Main Goals	Objectives	Reference of identified objectives
Ecological	Preserve resources	Preserve material resources/ Increase the use of renewable materials	(Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021)
		Save energy	(Abeysundra et al., 2007; Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004; Zuo & Zhao, 2014)
		Save water/ Protect water sources	(Hossaini et al., 2014; Peuportier et al., 2013)
		Reduce land use/transformation	(Peuportier et al., 2013)
	Protect the ecosystems	Limit toxic and hazardous emissions/ Reduce the use of toxic materials	(P. O. Akadiri et al., 2013a; Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004)
		Protect the climate	(Abeysundra et al., 2007; Peuportier et al., 2013)
		Protect the forests	(Peuportier et al., 2013)
		Protect rivers and lakes	(Peuportier et al., 2013)
		Improve outdoor air quality/ Limit Carbon Emissions	(Peuportier et al., 2013; Sahlol et al., 2021)
		Protect fauna and flora/ Habitat alterations	(Hossaini et al., 2014; Peuportier et al., 2013)
		Reduce waste and proper disposal of waste/ Reuse and recycle materials	(P. O. Akadiri et al., 2013a; Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004)
		Reduce radioactive waste	(Peuportier et al., 2013)
		Preserve and protect the ozone layer	(Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021)
		Limit floods	(Peuportier et al., 2013)
Economic	Reduce life cycle cost(P.	Reduce construction cost and affordability	(Abeysundra et al., 2007; Hossaini et al., 2014;

	O. Akadiri et al., 2013a; Hossaini et al., 2015; Seo et al., 2004)		Peuportier et al., 2013; Sahlol et al., 2021)
		Reduce operation cost / Cost saving due to reduced energy use	(Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Zuo & Zhao, 2014)
		Reduce maintenance cost	(Peuportier et al., 2013; Sahlol et al., 2021)
		Improve durability	(P. O. Akadiri et al., 2013a; Lee et al., 2013; Sahlol et al., 2021)
		Reduce renovation cost	(Peuportier et al., 2013)
		Reduce demolition cost/ Disposal Cost	(Peuportier et al., 2013; Sahlol et al., 2021)
	Add value	Facilitate space alteration	(Peuportier et al., 2013)
		Facilitate use alteration	(Peuportier et al., 2013)
Social	Preserve residents' health(Hossaini et al., 2014; Sahlol et al., 2021)	Improve indoor air quality	(Peuportier et al., 2013)
		Improve the quality of water	(Peuportier et al., 2013)
		Reduce risk of radiation	(Peuportier et al., 2013)
		Minimize risks and improve safety conditions	(Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Zuo & Zhao, 2014)
	Improve comfort (Hossaini et al., 2014)	Improve visual comfort and aesthetic appearance	(Abeysundra et al., 2007; Peuportier et al., 2013; Sahlol et al., 2021)
		Improve thermal comfort	(Abeysundra et al., 2007; P. O. Akadiri et al., 2013a; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004)
		Reduce noise	(Peuportier et al., 2013)
		Reduce odors/ Improve Air Quality	(Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021)
		Improve well being	(Peuportier et al., 2013)
	Add social value	Improve the quality of use	(Peuportier et al., 2013)
		Improve social and gender equity	(Peuportier et al., 2013)

		Integrate the disability issues	(Peuportier et al., 2013)
		Ease social relationships	(Peuportier et al., 2013)
		Improve participation/ Labour availability	(Peuportier et al., 2013; Sahlol et al., 2021)
		Accepted and embedded in the society	(Lambrechts et al., 2019; Zuo & Zhao, 2014)
Cultural	Develop creativity	Improve architecture and image	(Peuportier et al., 2013)
		Improve site integration	(Peuportier et al., 2013)
		Support cultural activities	(Peuportier et al., 2013)
	Conserve cultural heritage	Conserve historical sites	(Peuportier et al., 2013)
		Consider conserving or transforming existing buildings	(Peuportier et al., 2013)
		Conserve local regional materials	(P. O. Akadiri et al., 2013a; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004)
Technical	Technical Efficiency of construction work	Ease of construction	(Abeysundra et al., 2007; Sahlol et al., 2021)
		Reduced time for construction	(Abeysundra et al., 2007)
		Material availability	(P. O. Akadiri et al., 2013b; Sahlol et al., 2021)
	Technical Efficiency during the long run	Maintainability	(Sahlol et al., 2021)
		Resistance to Decay	(Sahlol et al., 2021)

2.3 **Sustainable Buildings and materials**

Sustainability enables one to meet current requirements without sacrificing the ability of future generations to satisfy their own (Hossaini et al., 2014; Peuportier et al., 2013; Troyer, 1990). Sustainability is emerging as a popular concept in recent times as allowing a pathway for a desirable society (Holden et al., 2014). In order to rectify all the global issues, the concept of "Sustainable development" is highly essential (Dimitrokali et al., 2010; Hossaini et al., 2014). The building industry is in essential need of proposing frameworks in order to develop a sustainability assessment due to the rapid growth of construction (Hossaini et al., 2014).

Akadiri et al., (2013) have mentioned that the current methods of selection of building materials do not satisfy the major sustainability issues and the authors stated that material framework is an important strategy to propose sustainable building material selection (P. O. Akadiri et al., 2013a). Ortiz et al. (2010) have stated that in order to be truly sustainable, the selection methods should be recast under the sustainability umbrella considering environmental, economic, social, and technical aspects (P. O. Akadiri et al., 2013a; Ortiz et al., 2010). Omer & Noguchi, (2020) have proposed a conceptual framework for understanding the contribution of building materials in order to achieve Sustainable Development Goals (SDGs) (Omer & Noguchi, 2020). They revealed that the building materials have a greater contribution to achieving several Sustainable Development Goals (SDGs) and have emphasized the use of a multi-criteria tool for material selection.

Buildings have more environmental effects, both direct and indirect. Buildings utilize energy, water, and raw materials during various stages like construction, occupancy, refurbishment, repurposing, and demolition. They also produce trash and emit potentially dangerous air emissions. As a result, there are already emerging green building standards, certifications, and rating systems that seek to reduce the negative effects of buildings on the environment through sustainable design. Various countries developed several guidelines and rating systems that can be used to guide and assess construction projects. Some such systems are “Leadership in Energy and Environmental Design” (LEED), “Building Research Establishment Environmental Assessment Method” (BREEAM), “Green Mark” (GM), “Building Environment Assessment Method” (BEAM), “Assessment Standard for Green Building” (ASGB), “Comprehensive Assessment System for Built Environment Efficiency” (CASBEE), “German Society for Sustainable Building” (DGNB), “High-Quality Environmental Standard” (HQE), EEWH(GBRT in Taiwan), and “Green Star” (GS) (Wen et al., 2020). Sahlol et al. (2021) have considered five international, national, and regional rating systems such as “Green Pyramids” (Egypt), “PEARL” (United Arab Emirates), “LEED” (United States), “BREEAM” (United Kingdom), and “Green Globes”

(Canada) in order to consider a vast diversity of cases and have tabulated the parameters as in a summarized form (Sahlol et al., 2021). The authors have introduced a group summation indicating the number of rating systems out of the considered ones consisting of each parameter. Accordingly, waste management, recycling of materials, use of local materials, and durability are ranked as important at a higher level while resource reuse and use of salvage materials, and use of certified wood fall under the next level. Though the different Green Building rating Systems (GBRS) have been developed in different parts of the world under different contexts, material selection becomes a common concern emphasized by all while contributing directly or indirectly to sustainability (Sahlol et al., 2021). The rating systems are usually frameworks with scoring systems.

Wen et al. (2020) have unified ten GBRSs and have presented three levels, namely, categories, subcategories, and criteria where the categories identified are environmental, economic, and social qualities (Wen et al., 2020). Several criteria and indicators were concluded under the mentioned categories. The summary of parameters provided by the authors clearly shows that material usage creates a greater impact on achieving green buildings. The life cycle thinking-based approach is a very useful concept that could be used to compare and select building materials over the long run (Gurupatham et al., 2021).

2.4 **Life Cycle thinking-based approach and sustainability**

The life cycle thinking approach is a cradle-to-grave approach that considers all stages of building life and supports the material selection in a better way. It could be considered when evaluating costs and impacts throughout the life of a building (Lu et al., 2017). Several countries with varying climatic conditions utilize the above concept in applications such as cost, performance, consumption of energy, impact on human health, and environmental issues over the long run (Gurupatham et al., 2021; Jun et al., 2019). Various concepts could be applied from a life cycle perspective in order to encourage a better selection of materials (Bruce-Hyrkäs et al., 2018).

Life cycle cost (LCC) is the cost that includes the costs incurred at all stages from the extraction of raw materials for production to the end of life (Gurupatham et al., 2021; S. Li et al., 2020). It could be used to evaluate the economic performance of several investment alternatives over a specified period of commercial interest considering suitable economic factors (AbouHamad & Abu-Hamd, 2019; Bull, 2003; Dwaikat & Ali, 2018; Flanagan et al., 2005; Gurupatham et al., 2021; B. S. I. ISO, 2008; Kirk & Dell'Isola, 1995; Norman, 1990). The International Standard ISO 15686-5:2008 could be used to conduct LCC (Dwaikat & Ali, 2018; Gurupatham et al., 2021).

Life Cycle Assessment is a technique for an integrative approach of environmental assessment that is applied to evaluate the environmental performance of products and processes in most cases (Lu et al., 2017)(Gurupatham et al., 2021; Perera et al., 2017). LCA is carried out by following the ISO standards such as 14040 and 14044 (AbouHamad & Abu-Hamd, 2019; Ferrández-García et al., 2016; Gurupatham et al., 2021). Buildings for Environmental and Economic Sustainability (BEES), Life cycle (LC) Aid, Athena Eco-Calculator, SimaPro, and Athena Impact Estimator are some of the commonly used programs for LCA computations (Ferrández-García et al., 2016; Gurupatham et al., 2021; Lu et al., 2017).

Energy is one of the key aspects when it comes to sustainability. Buildings consume a considerable amount of energy at every stage of their lifetime and the building materials are responsible for a greater share of the energy consumed (Yüksek, 2015). Energy consumption takes place in the form of embodied as well as operational stages and leads to emissions as embodied and operational emissions (Gurupatham et al., 2021; Thevarajah et al., 2020). Emissions create a significant impact on ecology. Energy saving is much important in economic growth and social development (Yüksek, 2015). Hossaini et al. (2014) have concluded that the environmental performance of a building is highly dependent on service life energy (Hossaini et al., 2014). The choice of building materials contributes highly to thermal performance and thus contributes to energy consumption.

The concept of eco-efficiency combines the environmental as well as the financial impacts of products or systems over the entire life span (Perera et al., 2017). Lower costs with lower environmental impacts lead to a higher value of Eco-efficiency (Ferrández-García et al., 2016). Cost-effective and environmentally friendly alternatives are found when compared and ranked using eco-efficiency (Ferrández-García et al., 2016; Gurupatham et al., 2021; Perera et al., 2017, 2018).

In addition to economic and environmental aspects, the inclusion of social aspects leads to life cycle sustainability (Wen et al., 2020). Recent studies have carried out S-LCA (Social Life Cycle Assessment) as a measure of social impact (Yıldız-Geyhan et al., 2017). S-LCA is a social impact assessment method that accesses the social aspect of a project throughout its lifetime (Benoît-Norris et al., 2011). The impact categories such as health and safety, security, working conditions, human rights, and socio-economic repercussions could be considered examples of social aspects (Yıldız-Geyhan et al., 2017).

There are several tools available to improve material selection sustainably. Eco-design is such a tool. It is a concept that incorporates all the above aspects and leads to the achievement of Green Building certifications and environmental product declarations (Bruce-Hyrkäs et al., 2018). Several studies that focused on life cycle thinking have examined the eco-design concept (Bundgaard et al., 2017; Dalhammar, 2015; Malcolm, 2011). ISO 14006 defined Eco-design as the amalgamation of environmental aspects into product design and development to reduce adverse environmental impacts throughout a product's life cycle (I. S. O. ISO, 2011; Lambrechts et al., 2019). It is a very useful tool that sets minimum requirements for the performance of products (Hinchliffe & Akkerman, 2017). Although a very useful concept, the industry has been slow to adapt to eco-design principles (Dekoninck et al., 2016; Lambrechts et al., 2019).

Rossi et al. (2016) congregated the tools and methods frameworks after a thorough literature review which shows a growing interest in the implementation of eco-design (Rossi et al., 2016). The identified tools and methods are the keys to practicing eco-design that includes economic, ecological, social, and cultural parameters and thus contributes to sustainable development (Cicconi, 2020; Negny et al., 2012; Peuportier et al., 2013; Rossi et al., 2016). Lambrechts et al. and Zuo & Zhao describe the Key dimensions of Eco-Design as environmental/technological aspects, social aspects, and economic aspects (Lambrechts et al., 2019)(Zuo & Zhao, 2014). Recent literature has listed the goals and objectives of the eco-design concept (Lambrechts et al., 2019; Peuportier et al., 2013; Zuo & Zhao, 2014). Technological, managerial, and behavioral success factors collectively contribute to eco-design applications (Lambrechts et al., 2019). Energy saving is an important factor of eco-design that addresses many factors related to sustainability as it creates an impact in almost all sectors that could be considered under sustainable development (Peuportier et al., 2013). Hence, eco-design is a concept that includes the triple bottom line aspects of sustainability and could be identified as a suitable tool in order to select sustainable building materials.

2.5 Material selections with the aid of quantifiable methods

It becomes easy to compare materials based on quantifiable approaches. Experimental testing procedures, calculations, and quantification with the help of computer simulations are approaches to compare and select materials.

2.5.1 Experimental testing procedures

All over the world, a greater number of tests are associated with the construction industry and they are carried out to test the elements and building materials (Hoła & Schabowicz, 2010; K. Schabowicz, 2015; Krzysztof Schabowicz, 2021; Szewczak et al., 2020). Experimental testing procedures are a sub-set of sustainable material section methods (Szewczak et al., 2020). The materials are tested for specific applications. Flaws and defects are identified as a result of experimental tests (Krzysztof Schabowicz, 2021). The tests could be either non-destructive or semi-destructive or destructive (Krzysztof Schabowicz, 2021).

Strength and durability concerns could be easily quantified by performing experimental procedures. Kariyawasam & Jayasinghe (2016) have carried out the strength as well as durability testing of cement-stabilized rammed earth walling material that has enough strength and durability while having a lower embodied energy with the variation of soil material such as sandy laterite, gravelly laterite, and clayey laterite and have found that the sandy laterite is the best soil type out of the considered soil types (Kariyawasam & Jayasinghe, 2016). In order to select the proper soil types, quantifiable testing procedures have been followed. C. Jayasinghe et al. (2016) have tested the load-bearing properties such as compressive strength, flexural strength perpendicular to bed joints, and flexural strength parallel to bed joints for the composite masonry constructed with recycled building demolition waste and cement stabilized rammed earth using quantifiable testing procedures (C. Jayasinghe et al., 2016). Similarly, numerous examples could be found in the past literature on performing experimental testing procedures in order to select suitable building materials. Hence, the results of testing could be an easy method of ranking materials.

2.5.2 Calculations and computer simulations

Parameters like costs could be calculated. Also, previous experimental results, databases, and literature could be used to derive available data on various aspects and thus calculations based on them can lead to quantification.

AbouHamad & Abu-Hamd, 2019 have carried out a framework selection system in which reinforced concrete framing (RC), structural steel framing (SS), and cold-formed steel framing (CFS) were compared (AbouHamad & Abu-Hamd, 2019). The framework has been carried out with the aid of Life cycle cost and sustainability. The framework incorporates building information modeling and energy simulation in order the compare the alternatives in the case of LCA and LEED points that have been used to access sustainability. Accordingly, the final assessment results showed that the life cycle cost of CFS is nearly 22% lesser than the other materials when incorporating the revenue generated, and RC, SS, and CFS framings received 0, 2, and 5 credit points respectively. Monte Carlo simulation has been used to account for uncertainties and with the help of sensitivity analysis, the factors creating higher impact have been identified.

Hossaini et al. (2014) have performed a case study on Life Cycle Sustainability by Analytical Hierarchy Process (AHP) in order to propose a sustainability evaluation framework by including several environmental as well as socio-economic factors (Hossaini et al., 2014). For this purpose, two typical six-story concrete and wood-framed houses were selected. A cradle-to-grave approach had been followed in order to assess the sustainability performance indicators such as economic social and environmental aspects that are also known as triple bottom line (TBL) sustainability performance indicators of buildings. The impacts were aggregated using AHP into a unified sustainability index and were compared. Accordingly, the study concluded that in a region with milder weather, the performance of the building depends on service life rather than structural materials.

Halwatura & Jayasinghe (2009) have carried out a comparison of roofing and insulations with the aid of life cycle costs including initial and running costs and have compared the Net Present Value (NPV) (Halwatura & Jayasinghe, 2009). The authors have found that the roof slabs could have lower capital as well as running costs for the top floor of air-conditioned buildings using computer simulation with DEROB - LTH (Dynamic Energy Response Of Building) and cost studies.

Udawattha & Halwatura (2018) have used real-world study, simulation analysis, and validation to examine the thermal performance of walling materials such as burnt bricks (BB), hollow cement blocks (HCB), and mud concrete blocks (MCB) (Udawattha & Halwatura, 2018). A case study approach was used on actual buildings with the same plan form but with three different walling materials, and it was discovered that the thermal performance of a BB wall that is 0.150 m thick can be achieved just as well by substituting an MCB wall that is 0.143 m thick and a hollow CB wall that is 0.21 m thick. Due to a larger U value and comparatively superior thermal performance than other wall materials investigated in the study, the authors have eventually come to the conclusion that mud concrete block has a better structural cooling ability and thermal performance.

Udawattha & Halwatura (2017) have compared walling materials such as Brick, Hollow cement blocks, Cabook, and Mud concrete blocks with the aid of Life Cycle costs(Udawattha & Halwatura, 2017). They have used an energy accounting hierarchical structure to find the life cycle costs. They ranked the materials individually based on parameters such as Initial cost, Life cycle cost, Operational energy costs, Embedded energy, Environmental suitability, and Carbon footprint and also finally provided an overall ranking of the considered materials. The overall ranking shows that mud concrete block is the best material and hollow concrete block is performing the least.

Perera et al. (2017) have carried out a case study on the eco-efficiency analysis of recycled material for residential construction (Perera et al., 2017). The authors have compared three different alternatives for walling such as conventional wall system, conventional with Inculcated Concrete Foam (ICF) and Recycled Concrete Aggregate (RCA) concrete walls, and ICF and RCA concrete wall system. They calculated LCC and LCA scores and thus calculated the eco-efficiency in order to compare the alternatives and select the best alternative. It was concluded that conventional wall construction with ICF concrete and RCA-based concrete wall systems has the highest eco-efficiency among the selected three alternatives.

Ferrández-García et al. (2016) have carried out an eco-efficiency analysis of the entire life cycle of interior partition walls (Ferrández-García et al., 2016). The LCA methodology had been applied and suitable alternatives were chosen such that they fall under lower cost and lower environmental impact. The graphical method of Interpretation of environmental indicators against cost has been used as a way to identify the alternative with lower cost as well as lower environmental impact.

Gurupatham et al. (2021) have performed a comparison between walling materials for their performance over the long run (Gurupatham et al., 2021). The authors have compared the Compressed Stabilized Earth Block (CSEB) walling material with conventional materials such as Burnt clay bricks (BCB) and Cement sand blocks (CSB) for Life cycle costs as well as the life cycle impacts. They quantified the eco-efficiency ratios and ranked the alternative solutions based on them. The authors followed a case study approach in order to rank and compare the walling materials and concluded that CSEB material is performing better than the conventional materials considered.

Dissanayake et al. (2017) have compared the EPS wall panels with conventional materials such as Burnt clay bricks and Cement sand blocks based on embodied energy analysis. (Dissanayake et al., 2017). For that, a case study approach had been followed for a typical single-story house. They quantified the energy as well as the emissions and ranked the materials individually based on Embodied energy as well as equivalent carbon emissions due to embodied energy. The study concluded that EPS material is a better material than conventional materials when considering embodied energy and emissions.

Thevarajah et al. (2020) have carried out a comparison between EPS panels and conventional materials such as Burnt clay bricks and Cement sand blocks based on embodied energy and carbon footprint (Thevarajah et al., 2020). A two Storied Refuge

Space had been considered as the case study model in order to compare the above walling materials. In addition to the embodied energy and carbon footprint, the suitability of the material to resist the forces of nature and to ensure safety while minimizing the adverse effects on the environment were considered in the above study.

Thus, based on the aforementioned literature findings it could be found that several studies have utilized comparative tools such as calculations and energy simulations as criteria for building material selection. In case of encountering situations of combining two different parameters, methods such as quantifying to a common index, graphical representation, and overall rankings have been used. Moreover, the case study approach had been identified in most of the studies as an effective strategy to compare several alternatives.

2.6 **Combination of qualitative and quantitative methods for building material selection**

In addition to the quantifiable factors in order to compare personal preferences, survey-based approaches are used. Most of the time Social concerns such as thermal comfort, good interior (aesthetics), ability to construct fast, and durability are compared based on survey-based approaches (Abeysundra et al., 2007). Interviews, questionnaires, and on-site observation are better ways to identify user requirements. Product quality and performance could be improved by investigating the end-users at the early stages of building construction (Zhang et al., 2019). Some pieces of literature have emphasized building performances by integrating the User-Centered Design (UCD) approach into the building sector (Bullinger et al., 2010; Kurnianingsih et al., 2014; Zhang et al., 2019). In survey-based approaches, Multi-Criteria Decision Making (MCDM) is usually applied in forming a decision support system when several criteria are considered. Selective examples of material selection with the combination of quantitative as well as qualitative factors have been discussed in this section.

Abeysundra et al. (2007) have carried out an environmental, economic, and social analysis of materials for doors and windows in Sri Lanka from in life cycle perspective (Abeysundra et al., 2007). They have compared timber and Aluminium. The materials were compared individually with the aid of environmental, economic, and social scores. A survey-based approach had been followed in order to compare the social parameters. Hence, it was concluded that the timber element is much more favorable in environmental and economic terms while aluminum was socially favorable. Also, the authors suggested Analytical Network Process (ANP) be a better technique to combine the aspects and select the best material.

Emmanuel (2004) has considered a walling material comparison (Emmanuel, 2004). The author assessed the environmental suitability of the popularly used materials and alternative walling materials and quantified the three parameters such as embodied energy, life-cycle costs, and re-usability into one "Environmental Suitability Index" calculated for $10m^2$ of wall and the materials were ranked based on the above index. In addition to the quantifiable parameters survey-based approach has also been followed.

Mesa et al. (2020) have developed a Material Durability Indicator or MDI in order to compare and select alternative building materials by ranking the MDI value obtained (Mesa et al., 2020). The proposed MDI provides a balance between the durability and environmental impacts in selecting suitable materials from available alternatives. It incorporates chemical durability, mechanical durability, and environmental performance which have been calculated in separate formulas. The environmental performance has been computed based on energy consumption whereas the other factors were calculated using appropriate constant values for each material based on liked scale values.

In addition to assessing based on individual criteria or reducing to an index, Multi-Criteria Decision Making (MCDM) techniques have been used to combine several criteria that would affect suitable selections. Selective examples of the use of MCDM have been described.

Yang & Ogunkah (2013) have carried out A Multi-Criteria Decision Support System for the selection of low-cost green building materials and components with the aid of AHP by including general or site factors, economic factors, environmental factors, sociocultural factors, technical factors, and sensorial factors (Yang & Ogunkah, 2013).

Hence, it could be noted that the MCDM could be used to incorporate a wide range of factors for material ranking.

Rahman et al. (2012) developed a roofing material selection framework called 'Knowledge-based Decision Support system for roofing Material Selection and cost estimating' (KDSMS) (Rahman et al., 2012). The above selection framework is good for qualitative as well as quantitative knowledge which was collected from domain experts and other technical literature. TOPSIS (Technique of ranking Preferences by Similarity to the Ideal Solution) multiple criteria decision-making method has been used to solve materials selection and optimization problems.

Krawczyńska-Piechna (2017) has worked on formwork selection and thus has used MCDM methods for which the decisive criteria were obtained using a structured survey that was sent to contractors (Krawczyńska-Piechna, 2017). For that, the factors influencing the formwork selection have been obtained through past research works, and in order to unify the selection method, an expert survey had been used with the aid of a structured survey. The decisive criteria mentioned above were ordered using the Rank Exponent method (Krawczyńska-Piechna, 2017)

Alibaba & Özdeniz (2004) have worked on building element selection for which they have used an expert system shell called "Exsys Corvid"(Alibaba & Özdeniz, 2004). The SMART methodology has been used for this computer program for the selection of alternatives.

The selection of internal finishes plays a major role as the finishing materials have a greater impact on the sustainability aspects such as environmental, economic, and social (Castro-Lacouture et al., 2009; Zhang et al., 2019). Zhang et al., (2019) have worked on material selection for interior finishing (Zhang et al., 2019). They have identified that more than the quantitative indicators such as material energy performance and life expectancy, there are qualitative requirements like visual aesthetic preference. Hence, they have incorporated both quantitative and qualitative aspects and have proposed an immersive virtual reality (IVR) based approach for the selection of finishing materials. The proposed IVR includes both the aesthetics and conventional material performance where they have included multi-criteria decision-making (MCDM) analysis as well as interactive particle swarm optimization algorithm (IPSO)-based material collocation optimization.

Zha (2005) has proposed a web-based advisory system for process and material selection and has used a fuzzy knowledge-based decision support method for multi-criteria decision-making in order to select material combinations (Zha, 2005).

Hence, based on the aforementioned literature findings it could be observed that MCDM has been widely used considering both the quantitative as well as qualitative factors. Further research works that worked on finalizing sustainable material selection criteria are shown in Table 2. Similar methods could be followed to identify and finalize the themes and subthemes under the considered concept.

Table 2: Selective literature on finalizing material selection criteria

Authors and year of publication	Research work	Key objectives	Identification of themes and sub-themes under the concept	Determination of weights of themes and sub-themes	Comparison and ranking of alternatives
Akadiri et al. 2013 (P. O. Akadiri et al., 2013b)	“Multi-criteria evaluation model for the selection of sustainable materials for building projects “	To propose building material selection model based on Fuzzy Extended Analytical Hierarchy Process	- Identified through literature review - Finalized through an industry questionnaire survey with a sample size of 90 respondents - Quantified with Relative index	Pair-wise comparison of themes and sub-themes Application of FEAHP with 1 expert	Application of AHP technique with 1 expert Compared roofing elements
Sahlol et al. 2021 (Sahlol et al., 2021)	“Sustainable building material Assessment and selection using system dynamics”	To propose a set of parameters that affects selecting sustainable materials	- Identified through literature review - Finalized through expert opinions with a sample size of 96 - Quantified with Importance index	Pairwise comparison of 5 suitable parameters for the considered alternative materials	Application of AHP for 5 selective parameters Evaluation of Steel, concrete and wood

Amer & Attia 2019 (Amer & Attia, 2019)	"Identification of sustainable criteria for decision-making on roof stacking construction method"	To propose sustainable decision-making for roof stacking	- Identified through literature review - Finalized through semi-structured interviews with a sample size of 78 - Quantified with Severity index	-	-
Kamali & Hewage 2016 (Kamali & Hewage, 2016)	"Development of Performance Criteria for Sustainability Evaluation of Modular versus Conventional Construction Methods"	To identify Sustainable Performance Indicators suitable for modular and conventional construction methods	- Identified through literature review - Finalized through expert surveys with a sample size of 46 - Quantified with Severity index	-	-

2.7 Multi-Criteria Decision Making (MCDM)

For the past five decades, Multi-Criteria Decision Making (MCDM) has been identified as a suitable and efficient way to solve complicated problems with multi-criteria and several alternatives (Abdel-basset et al., 2019; Ho et al., 2010). MCDM methods have been recognized since the early 1970s by researchers (Abdel-basset et al., 2019). Several MCDM methodologies can be used to combine several inconsistent criteria. Some of the methods mentioned in the literature are the Multi-Objective Optimization based on Ratio Analysis (MOORA) (Brauers & Zavadskas, 2006, 2010), Analytic Hierarchy Process (AHP) (Thomas L Saaty, 2008), the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Abdel-basset et al., 2019). Qualitative as well as quantitative data from the alternative materials could be combined with the aid of MCDM methodologies. Many of the Multi-Criteria Decision Making (MCDM) are extended to group decision-making (Abdel-basset et al., 2019).

The MOORA method refers to the response matrix of alternatives to the target, applying ratios (Brauers & Zavadskas, 2006, 2010). In this method, each response of an alternative is compared to a target with a denominator that represents all the alternatives related to that objective (Brauers & Zavadskas, 2010).

AHP (Analytical Hierarchy Process) is being widely used in multi-criteria decision-making problems (P. O. Akadiri et al., 2013a; T L Saaty, 1980; Zavadskas et al., 2011). In order to approach sustainable selections, many researchers have used the APH method (P. O. Akadiri et al., 2013a; Nassar et al., 2003; Reza et al., 2011; Shapira et al., 2006; Ugwu et al., 2006; H. Wang et al., 2012; Wong & Li, 2008). There are four main steps involved in the structuring of a decision into AHP (P. O. Akadiri et al., 2013a; Thomas L Saaty, 2008; Zahedi, 1986). They are the definition of the material selection problem, identification of objectives, and recognition criteria and attributes. Accordingly, objectives, criteria, attributes, and the selected alternatives are considered from the first level to the fourth. Every level is compared using a nine-point scale indicating the level of importance in carrying out pair-wise comparisons and obtaining the judgmental matrix. The local weights are computed based on a judgmental matrix using an eigenvector and the consistency ratios are computed to check whether it falls within 0.1. The responses by human judgment are accepted when the consistency ratio is within 0.1. Then the local weights are aggregated in achieving the final weights. Several other studies have been conducted using the AHP method from which further details on AHP could be obtained (R. W. Saaty, 1987; T. Saaty & Shang, 2011; Shapira et al., 2006; Yang & Ogunkah, 2013). The above method is easy to be applied. However, uncertainty and ambiguity present in deciding the priorities of different attributes are not addressed in AHP which is said to be a drawback of the method (P. O. Akadiri et al., 2013a; Medineckiene et al., 2011). Also, the discrete scale may not be accurate to interpret human interpretations (P. O. Akadiri et al., 2013a; Jaskowski et al., 2010).

In order to rectify the above drawback, Medineckiene et al. (2011) stated that linguistic variables and triangular fuzzy numbers can be used (Joshi & Kumar, 2016; Medineckiene et al., 2011). Numerous MCDM methods use the fuzzy set or the intuitionist fuzzy set theories to overcome the above drawbacks (Abdel-basset et al., 2019). Hossaini et al., (2014) recommend, uncertainty analysis with the use of probabilistic and fuzzy-based methods for future studies (Hossaini et al., 2014). Fuzzy is commonly used in Group decision-making (D. F. Li & Yang, 2004; Ölçer & Odabaşi, 2005). In order to find out the final priority weights based on triangular fuzzy numbers; the Synthetic extent analysis method is applied. The above method is known as fuzzy extended AHP (FEAHP) (P. O. Akadiri et al., 2013a; Chan & Kumar, 2007).

TOPSIS is a useful and popular approach that could be applied by decision-makers in order to rectify the issues such as vagueness, incomplete data, and uncertainty (Abdel-basset et al., 2019; Nadaban et al., 2016). Fuzzy TOPSIS (Technique for Order Preference by Similarities to Ideal Solution) is one of the best methods in order to select the best material out of several options (Nadaban et al., 2016) that could automate the process and overcome ambiguity and uncertainty (Kore et al., 2017). The concept of fuzzy TOPSIS is such that the solution is nearest to the Positive Ideal Solution (PIS) and furthest to Negative Ideal Solution (NIS) (Nadaban et al., 2016).

2.8 **Summary**

The selection of building materials is becoming critical with several alternatives emerging recently. Quantifiable factor-based rankings are easily carried out using experimental testing procedures, calculations, software, and energy simulations. Qualitative factors are determined based on human judgments whereas questionnaire surveys and interviews are popularly used. Several factors could be identified as factors affecting sustainable development in the selection of building materials. When combining several factors that influence the material selection, Multi-Criteria Decision (MCDM) is popularly followed. AHP has been identified as a popular tool in order to find the weightage of factors affecting material selection as well as it is used to the extent of selecting from several alternatives. In order to rectify the drawbacks in AHP, several other MCDM approaches such as fuzzy numbers, and the TOPSIS method are recommended which could lead to better decision-making when selecting building materials.

Since both quantitative and qualitative parameters are involved in sustainable material selection, multi-criteria decision-making could be recommended as a suitable measure that combines various parameters.

3. QUESTIONNAIRE SURVEYS: DESIGN AND PROCESS

The data collection was mainly carried out using surveys and expert interviews in addition to a literature review. The surveys were carried out to evaluate the level of importance of sub-themes of eco-design and finalize the sub-themes, to carryout pairwise comparison of themes and sub-themes and develop the framework and compare the alternative materials concerning each sub-theme in order to apply the framework into a case study. The conducted surveys are elaborated on in sections 3.1 to 3.3.

3.1 Survey on the level of importance of sub-themes

A survey on the level of importance of sub-themes was prepared with the knowledge obtained through the literature review including the themes and sub-themes that are identified through the literature review. As a result, the themes such as Ecological, Economic, Social, and Cultural were identified. Under each theme, suitable sub-themes were listed. Then, the survey on the level of importance was prepared. The design of the questionnaire, pilot survey, selection and approach of respondents, and analysis methods are elaborated under sections 3.1.1 to 3.1.4.

3.1.1 Design of Questionnaire and Pilot survey

Firstly, a pilot survey was conducted to obtain the opinion on the level of importance of identified sub-themes of eco-design (Questionnaire on eco-design building material selection in Sri Lanka) among a group of experts. The surveys were conducted as interviews with one-to-one interaction. The experts were approached and interviews via an online platform were arranged in order to obtain an efficient response. The team of experts consisted of two chartered engineers who are working in the industry and four academics who have expertise in Green Projects including the disciplines of Architecture and Civil Engineering. Among the approached experts, 4 of them were Accredited Professionals (APs) of the Green Building Council of Sri Lanka (GBCSL) while one of them was an AP of GBCSL, LEED, and BREEAM. They had varying years of experience in green projects and have been involved in various projects. The analysis of the survey respondents of the pilot survey is interpreted in Figures 2 to 5.

After the interviews, the sub-themes were concluded. The result of the above discussions showed that all the identified sub-themes are either important or very important while further sub-themes were suggested to be added. The suggested sub-themes are applicability with the fundamentals, water efficiency, reducing heat island effect, cost saving by reuse and recycling, local availability for reducing foreign exchange, aesthetic appearance, and local sourcing of raw materials for Improving employment opportunities. Also depending on their opinions and suggestions, the survey was further improved. Then the survey was conducted among the targeted respondents who are experts in the field. The opinion of the respondents on the level of importance of each sub-theme identified had been noted down on a Likert scale from 1 to 5 representing Not Important to Very Important respectively. The Likert scale used to find the level of importance of the sub-themes has been presented in Table 3.

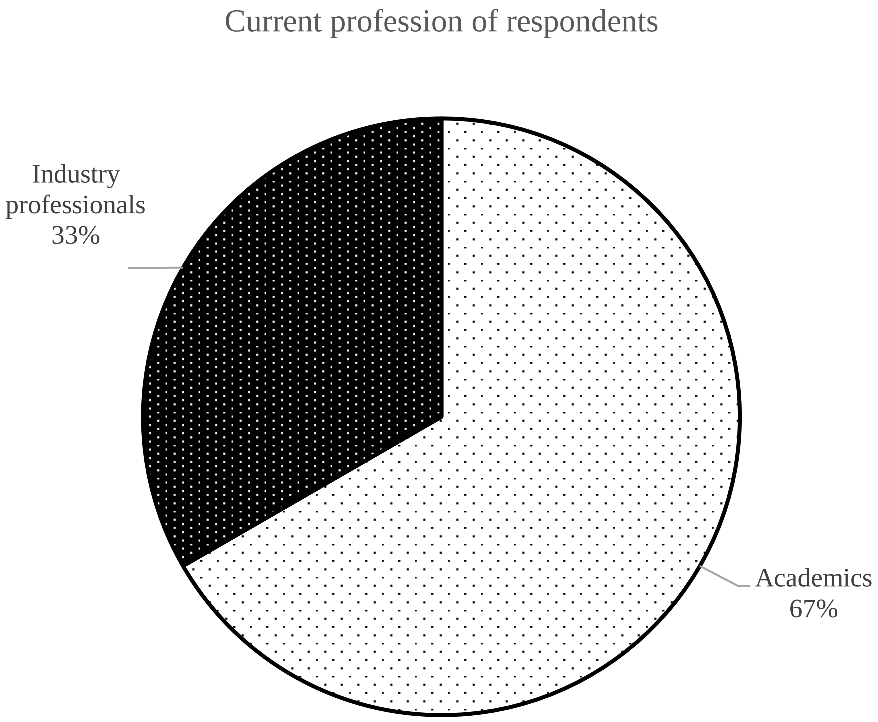

Figure 2: Current Profession of pilot survey respondents

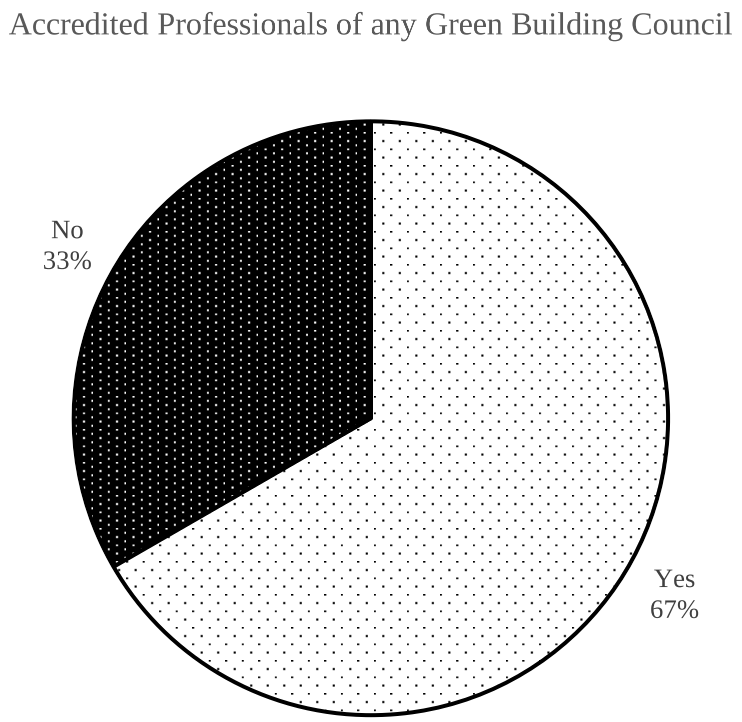

Figure 3: Pilot survey respondents whether Accredited Professionals or not

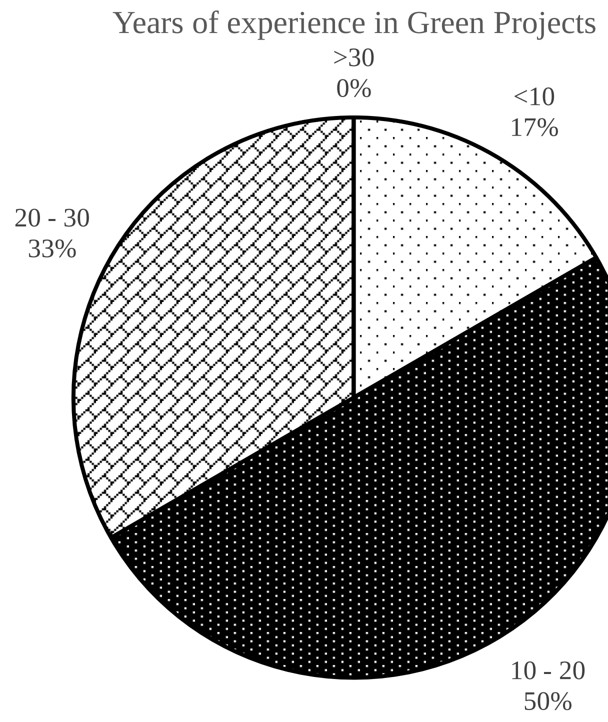

Figure 4: Years of experience in Green Projects of pilot survey respondents

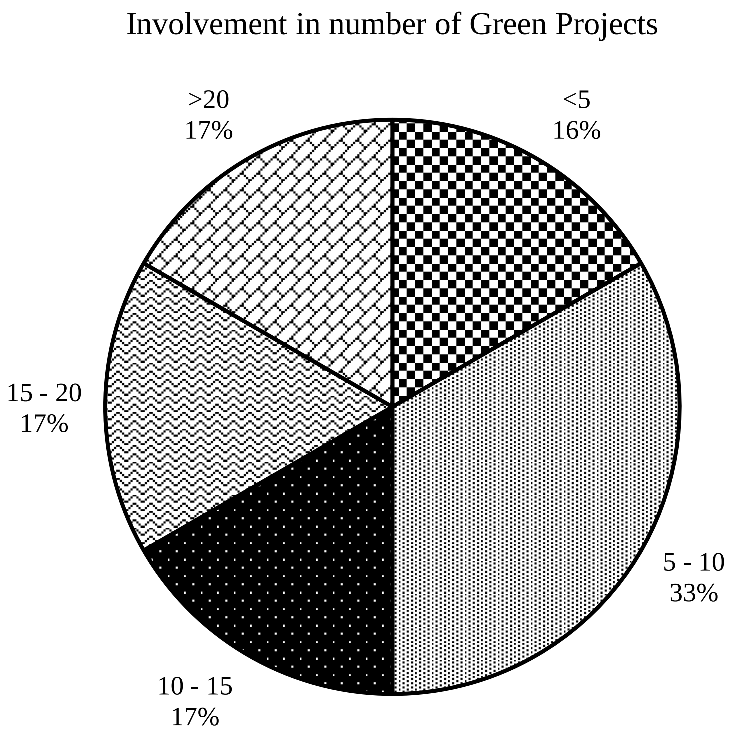

Figure 5: Involvement in number of Green Projects by the pilot survey respondents

Table 3: Likert scale for level of importance

Value on the Scale	Description
1	Not Important
2	Less Important
3	Neutral
4	Important
5	Very important

3.1.2 Respondents to the survey

It was observed through the pilot survey that APs of any Green Building Councils involved themselves in green projects and thus, their experience in the discipline of Sustainability and Building materials has been greater compared to Non-Accredited Professionals (NAP). Hence, the respondents were chosen such that they are APs of any Green Building Councils. In order to expand the scope and to generalize the results of the study for Tropical climatic conditions, APs of both GBCSL and IGBC (Indian Green Building Council) were chosen. Accordingly, the survey had been conducted among a group of professionals consisting of Engineering or Architecture professional backgrounds while holding various positions such as Architects, Design Engineers, Project Engineers, Operation Engineers, Mechanical Engineers, Electrical Engineers, Managing Directors, Green Building Consultants, Sustainability consultants, Councilors, CEOs of construction companies, Chairman and officials of Green Building Councils and Academics including Professors, Lecturers, and Researchers who are working towards the sustainability aspects who are APs. Furthermore, the survey was improved continuously while conducting surveys.

3.1.3 Process of survey

Surveys were planned in the form of interviews with one-to-one interaction in order to find out personal opinions regarding the level of importance. Hence, the professionals are initially approached through email in order to contact and schedule meetings. Accordingly, the questionnaire was prepared in PDF version to be attached with the request emails for participation in the surveys. This was carried out in order to ensure that the participants get a basic idea about the survey to be conducted before the interviews. The questionnaire was sent to over 100 people and contacted by phone, followed by two reminder emails to schedule a meeting. The connections were expanded through the known contacts to reach their peers who are experts in the field. All the meetings have been conducted via the online platform.

3.1.4 Quantification of the level of importance

The level of importance of each sub-theme was quantified using the Relative Index (O. P. Akadiri, 2011; P. O. Akadiri et al., 2013b; Braimah & Ndekugri, 2009; Ezekiel A. et al., 1998; Olomolaiye et al., 1987). The equation for the relative index is provided in Equation 1. The sub-themes were concluded with the aid of Relative Index values and then the themes and the finalized sub-themes were subjected to pair-wise comparison through the survey. The Relative Index was transferred to 5 important levels to classify the level of importance of the sub-themes. The range of the Relative Index (RI) and respective descriptions are provided in Table 4 (O. P. Akadiri, 2011; P. O. Akadiri et al., 2013b).

$RI = \sum w/ AxN$ --Equation 1

Where,

w: Weighting as assigned by each respondent on a scale of one to five with one implying the least and five the highest

A: Highest weight

N: Total number of the sample

Table 4: Range of Relative Index and description

Range of Relative Index	Description	Symbol
(0.8≤RI≤1)	High	H
(0.6≤RI<0.8)	High–Medium	H – M
(0.4≤RI<0.6)	Medium	M
(0.2≤RI<0.4)	Medium–Low	M – L
(0≤RI<0.2)	Low	L

3.2 **Survey on pairwise comparison**

The questionnaire survey on pairwise comparison focused on collecting opinions on themes and sub-themes in order to achieve eco-design practices and propose weights for the themes and sub-themes. The design of the questionnaire, the selection and approach of respondents, and the quantitative techniques followed are elaborated in sections 3.2.1 to 3.2.4.

3.2.1 Design of questionnaire

The experts were expected to compare the themes and sub-themes with one another indicating the level of importance over the other on a Likert scale from 1 to 9 where 1 indicates that they are of equal importance and 9 indicates that one is showing extreme importance over the other. The Likert scale is provided in Table 5 (O. P. Akadiri, 2011). Accordingly, the themes and the sub-themes under each theme are compared pair wisely.

Table 5: Likert scale for pair-wise comparison

Value on the Scale	Description
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

3.2.2 Selection of respondents and the process of the survey

A group of respondents for the Survey on Pairwise Comparison of Themes and Sub-themes were selected such that they have more years of experience in Green Projects and have been involved with a greater number of Green Projects. Moreover, the literature states that it is not mandatory to have a larger sample size in order to carry out Analytical Hierarchy Process (O. P. Akadiri, 2011). Also, a bigger sample leads to excess information and becomes difficult to handle thus, the recommended sample size is 6 to 12 participants (Melón et al., 2008). The data collected from the survey on the level of importance of sub-themes on their level of experience had been analyzed to choose experts for the survey on the pairwise comparison. Accordingly, 11 experts were chosen and approached for the above survey. The approached respondents had greater than 10 years of experience in green projects and had been involved in greater than 10 projects. A Delphi approach has been practiced in order to obtain a consensus on the opinion of the participants (Ogbeifun et al., 2016)

3.2.3 Delphi technique

The Delphi technique is a research method that reaches a general agreement on the opinions of the participants (Grisham, 2009; Ogbeifun et al., 2016). When following this technique participants are allowed to change their opinion from one round to the other. This is seen as a strength of the Delphi technique. The selection of the panel of experts and effective communication are given much importance in carrying out this method (Ogbeifun et al., 2016). The participants are purposely chosen to be experts in the field of study using pre-qualification criteria rather than reaching out to a random sample to improve the quality of the responses and consented to their willingness to contribute to the multiple rounds of interactions (Day & Bobeva, 2005; Grisham, 2009; Hallowell & Gambatese, 2010; Hasson & Keeney, 2011; Ogbeifun et al., 2016; Xia & Chan, 2012). The participants and their opinions are kept in confidence and the participants were traceable with their responses (Franklin & Hart, 2007; Ogbeifun et al., 2016). The number of participants could be a minimum of 3 members to a maximum of 80 members (Grisham, 2009; Mullen, 2003; Ogbeifun et al., 2016). All 8 experts contributed and supported the iterative process. Effective engagement was ensured through one-on-one interactions (Day & Bobeva, 2005; Donohoe & Needham, 2009; Ogbeifun et al., 2016). The number of rounds of iteration was carried out till the stage where the participants are no longer changing their opinions (Franklin & Hart, 2007; Ogbeifun et al., 2016). Then, the finalized responses on the pairwise comparison were subjected to Analytical Hierarchy Process (AHP).

3.2.4 Analytical Hierarchy Process

Akadiri et al. (2013), Nassar et al. (2003), Reza et al. (2011), Shapira et al. (2006), Ugwu et al. (2006), H. Wang et al. (2012), and Wong & Li (2008) have used AHP for comparisons, and Akadiri et al. (2013), T L Saaty (1980), and Zavadskas et al. (2011) have mentioned that it is a popular and useful method to be followed in multi-criteria decision-making problems (P. O. Akadiri et al., 2013a; Nassar et al., 2003; Reza et al., 2011; T L Saaty, 1980; Shapira et al., 2006; Ugwu et al., 2006; H. Wang et al., 2012; Wong & Li, 2008; Zavadskas et al., 2011). AHP is used here to finalize the themes and the subthemes and provide weightage of each theme and sub-theme in contributing to the eco-design material selection framework. The process consists of 4 levels such as material selection problem, themes or objectives, Sub-themes or criteria under each theme and the alternative materials to be ranked (P. O. Akadiri et al., 2013a; Thomas L Saaty, 2008; Zahedi, 1986). Each level in the hierarchy is compared by a nine-point scale shown in Table 3 pair-wisely to obtain a judgmental matrix. The consistency is checked by ensuring whether the consistency ratio of each response falls less than 0.1 (O. P. Akadiri, 2011; P. O. Akadiri et al., 2013b). The Consistency Ratio is calculated by following equations 2 to 5.

The comparisons among the themes and the sub-themes are carried out as pairs forming square matrices $(n\times n)A=[a_{ij}]$, such that (Jaskowski et al., 2010; T L Saaty, 1994);

$a_{ij}=1/a_{ji}$ *and* $a_{ii}=1$ for each $i,j=1\ldots n$ ----------------------------------Equation 2

The equation for priority vector w is such that (Jaskowski et al., 2010; Karayalcin, 1982);

$Aw=\lambda_{max}\,w$--Equation 3

Where λ_{max} is the principal Eigenvalue of A;

Then the Consistency Index *(CI)* is calculated using Equation 4 (Jaskowski et al., 2010; Karayalcin, 1982; Thomas L Saaty, 1990).

$CI = (\lambda_{max} - n)/(n-1)$ --Equation 4

Finally, the Consistency Ration *(CR)* is computed using Equation 5 (Jaskowski et al., 2010; Karayalcin, 1982).

$CR = CI/R$ ---Equation 5

Where RI values are shown in Table 6 (Ammarapala et al., 2018; T L Saaty, 1980). The responses are then aggregated to find the final weights.

Table 6: RI values with the size of the matrix

Matrix Size	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random Consistency Index (RI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Source: (Ammarapala et al., 2018; T L Saaty, 1980)

3.3 **Testing of the developed framework**

The proposed framework was applied to the case study. Accordingly, Cement Stabilized Earth Blocks (CSEB) have been compared with Burnt Clay Bricks (BCB) and Cement Sand Blocks (CSB). The description of the case study model house has been provided in section 3.3.1. Further, some of the finalized sub-themes are quantitative whereas the rest are qualitative. The quantitative parameters are obtained through a case study model house while the other parameters are quantified with the aid of expert interviews. A Multi-Criteria- Decision Making Method (MCDM) called TOPSIS had been made used to combine all the sub-themes and to compare the materials. The computed values and quantified parameters with the aid of discussions with a group of experts and the TOPSIS application are elaborated in sections 3.3.2 to 3.3.4.

3.3.1 Case study

A simple house plan with a $65m^2$ floor space that is situated in the Ratmalana neighbourhood of the District of Colombo, Sri Lanka, has been chosen, and the study has been performed. The climatic information for Ratmalana has been entered into Design Builder as Ratmalana was assumed to be the site of the house. Figure 6 depicts the floor plan of the considered model house. The thermal efficiency of the building is significantly influenced by the building's orientation. It could be chosen depending on the wind and sun radiation directions as well as aesthetics, views, and privacy needs (Jayasinghe, C. and Jayasinghe, 2009). The model house was built with its orientation chosen so that the entrance faces South. Due to Sri Lanka's proximity to the equator, walls facing East and West are more likely to receive radiation from the sun. Therefore, there is a potential of receiving intense solar radiation as the model house is situated so that the longer walls are facing East and West directions. However, the apertures face North and South, and the amount of solar radiation that enters the structure is reduced, which lowers the temperature of the inside air (Jayasinghe, C. and Jayasinghe, 2009).

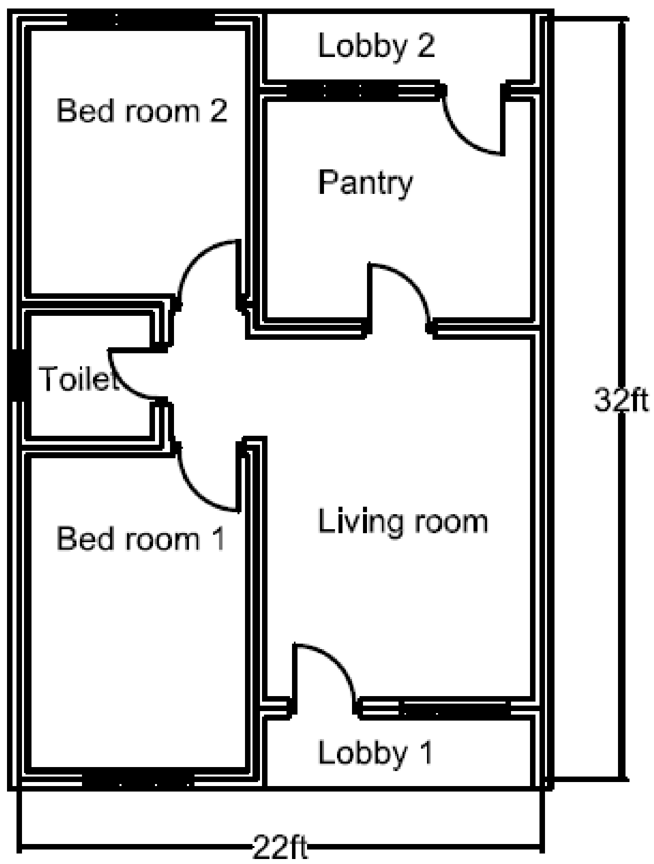

Figure 6: Plan view of the sample house considered

Source: (Gurupatham et al., 2021)

The case study was carried out as a comparative study, in which the performances of the walling materials are compared and all the aspects and factors are continuously presented. The materials that were considered for the house's other components, however, are described.

Burnt clay tiles are the roofing material taken into account by the model. Wood is considered for windows and doors. Aside from the enclosing materials, other materials utilized include concrete for the foundation and floor, asbestos sheets for the ceiling, ceramic tiles for the floor finish, and light-colored paint, like white, to finish the plastered walls.

The house is anticipated to hold three occupants, with two people sharing the master bedroom and one person occupying the other bedroom. Here, it is assumed that the rooms have air conditioning that runs from 9 p.m. to 5 a.m. every day and provides air at a temperature of 240^{0}C with a humidity ratio of 0.008, which is within the comfort range when a psychrometric chart is drawn with a suitable neutrality temperature for the area under consideration (Jayasinghe, C. and Jayasinghe, 2009; *Jayasinghe, M. T. R.,"Energy Efficient Houses for Tropical Climates", MacBolon Polymer , Sri Lanka , 180 p, 2003 (ISBN 955-8872-00-8)*, n.d.). Air changes per hour must be within the range of 0.5 and 4 (Jayasinghe, C. and Jayasinghe, 2009). Thus, mechanical ventilation with the requisite minimum fresh air has been provided for the air-conditioned space during the period of air conditioning, while an air change of 3ach has been provided for the naturally ventilated sections. When air conditioning is being used, the house's air-conditioned areas are airtight.

Only the walling material was altered in all of the models, keeping the other building components and environmental factors unchanged. Burnt clay bricks (BCB), cement sand blocks (CSB), and Compressed Stabilized Earth Blocks (CSEB) are the walling materials that are taken into consideration. The walls have been presumed to be load-bearing walls that are one brick thick. The Design Builder model of the house is presented in Figure 7.

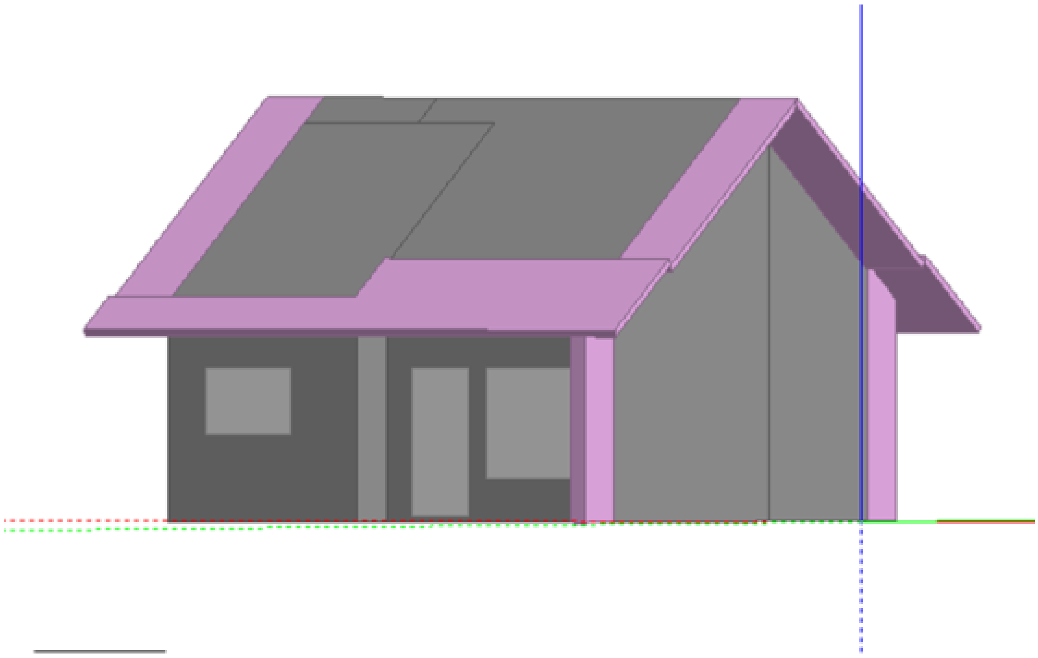

Figure 7: House modeled in Design Builder

Source: (Gurupatham et al., 2021)

3.3.2 Quantified parameters with the aid of a model house

Gurupatham et al. (2021) have compared Cement Stabilized Earth Blocks (CSEB) with Burnt Clay Bricks (BCB) and Cement Sand Blocks (CSB) and have quantified the parameters such as Total life cycle energy, Total life cycle emissions, Initial construction cost, Operational energy cost for a year, Maintenance Cost Per year and Required cooling load for comfort criteria which could be used for the sub-themes such as Saving energy, Reducing energy emissions, Reducing construction cost and increasing affordability, Reducing operational cost and cost saving due to energy reduction, Reducing maintenance cost and Improving thermal comfort respectively (Gurupatham et al., 2021). The authors have quantified the parameters for the considered case study model house elaborated under section 3.3.2.

3.3.3 Quantified parameters with the aid of expert interviews

The comparison of the walling materials with respect to the remaining sub-themes has been carried out with the aid of discussions with a group of experts. A five-point scale provided in Table 7 has been utilized to compare the materials with respect to the qualitative sub-themes. Then TOPSIS has been applied in order to combine the quantitative as well as qualitative aspects.

Table 7: Five-point scale for material comparisons

Likert Scale	Description
1	Low
2	Below average
3	Average
4	Good
5	Excellent

3.3.4 Technique for Order Preference by Similarities to Ideal Solution (TOPSIS)

TOPSIS is one of the best techniques that leads to better material selection out of alternatives that help to overcome issues like ambiguity and uncertainty (Kore et al., 2017; Nadaban et al., 2016). It has been used to compare and rank alternative materials. The important steps followed in finding the best alternative are normalization, weighting, determining the positive and negative solutions, finding out the distances from the positive Ideal Solution and Negative Ideal solution, computing the relative closeness to the Positive Ideal Solution and Negative Ideal Solution and ranking the alternatives from best to the worst (Corrente & Tasiou, 2022). The relevant formula is provided in Equations 6 to 12

In each criterion $g\ j\ \in G$ and for each $ai\ \in A$, the normalized value of aij (zij) is calculated using Equation 6.

$$z_{ij} = \frac{aij}{\sqrt{\sum_{i=0}^{n} aij^2}} \text{--Equation 6}$$

Weighting $w=[w_1,..., w_m]$, the vector composed of the importance of criteria in G, such that $w_j>0$ for all $g_j \in G$ and $\sum_{j=1}^{m} wj = 1$ for each $g j \in G$ and for each $a_i \in A$; the normalized weighted value v_{ij} is calculated using Equation 7.

$$V_{ij}=z_{ij}.w_j \text{--Equation 7}$$

The Positive Ideal Solution (PIS); denoted as G_I and the Negative Ideal Solution (NIS); denoted as G_D are computed using Equations 8 and 9.

$$PIS = A^+ = (v_1^+, \ldots, v_m^+) \text{ where } v_j^+ = \begin{cases} \max v_{ij} \text{ if } g_j \in G_I, \\ i=1,\ldots,n \end{cases} \text{-----------------Equation 8}$$

$$NIS = A^- = (v_1^-, \ldots, v_m^-) \text{ where } v_j^- = \begin{cases} \min v_{ij} \text{ if } g_j \in G_I, \\ i=1,\ldots,n \end{cases} \text{-----------------Equation 9}$$

For each $a_i \in A$ the distance from PIS and NIS; denoted by $d^+(a_i)$ and $d^-(a_i)$ are computed using Equations 10 and 11.

$$d^+(a_i) = \sqrt{\sum_{j=1}^{m}(vij - v_j^+)^2} \text{---Equation 10}$$

$$d^-(a_i) = \sqrt{\sum_{j=1}^{m}(vij - v_j^-)^2} \text{---Equation 11}$$

For each $a_i \in A$ the relative closeness C(ai) to the PIS and NIS (Performance score) is calculated using Equation 12.

$$C(a_i) = \frac{d-(ai)}{d-(ai)+d+(ai)} \text{--Equation 12}$$

4. ANALYSIS AND RESULTS OF SURVEY RESPONSES

The analysis and results of the responses to the survey on the level of importance of sub-themes, the Survey on pair-wise comparison of themes and sub-themes, and the application to the case study have been elaborated under sections 4.1, 4.2, and 4.3 respectively.

4.1 Survey on the level of importance of sub-themes

A sample of respondents was analyzed by comparing their years of experience, professional disciplines, participation in industrial projects, and Nationality of respondents. The professional discipline, occupation type, and accredited professional membership details are expressed in Figures 8 to 11. The years of experience in Green Projects and the number of green projects involved by the respondents are presented in Figures 12 and 13. Analysis of the respondents shows that 21% of the respondents are having an experience over 10 years in Green Projects and have worked with more than 10 Green Projects.

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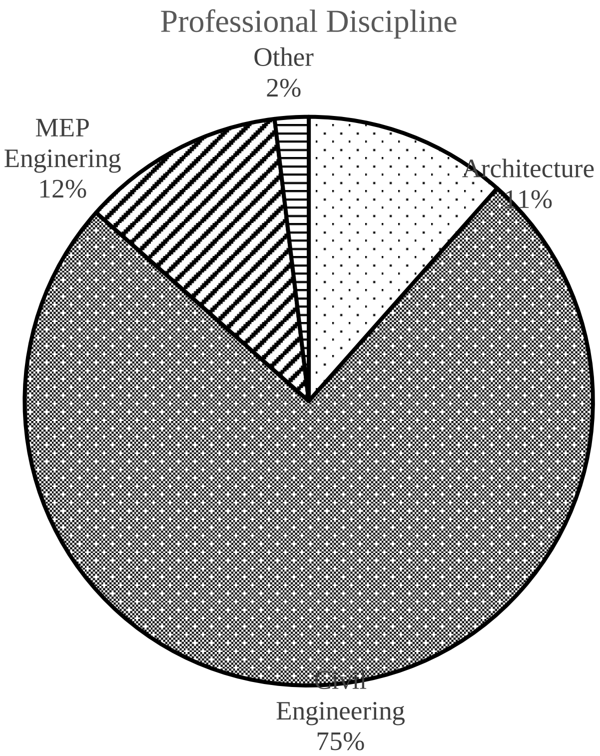

Figure 8: Professional discipline of survey respondents

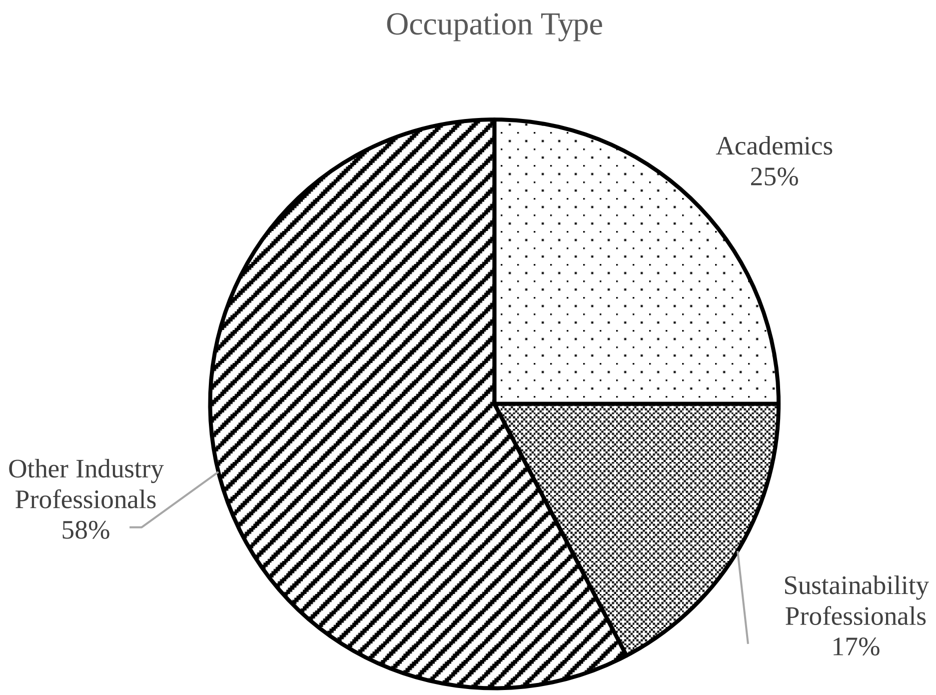

Figure 9: Profession of survey respondents

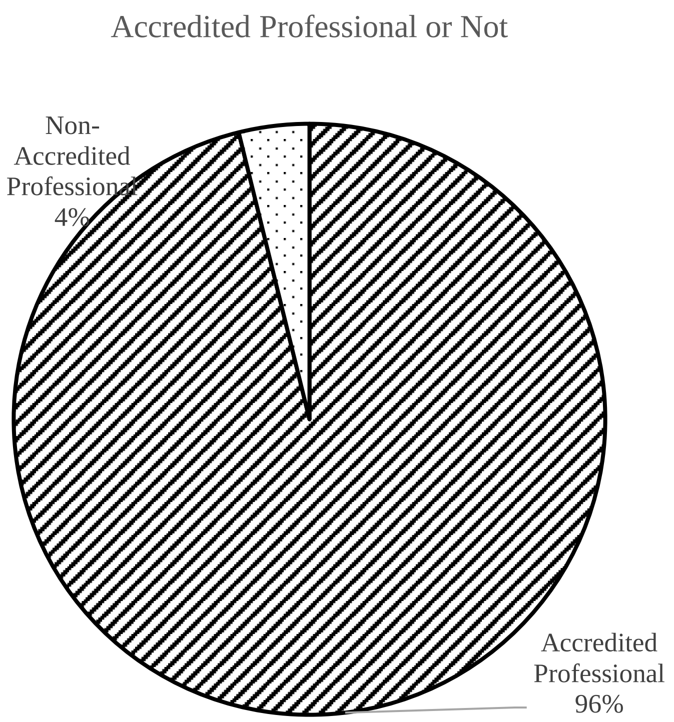

Figure 10: Survey respondents whether accredited professionals or not

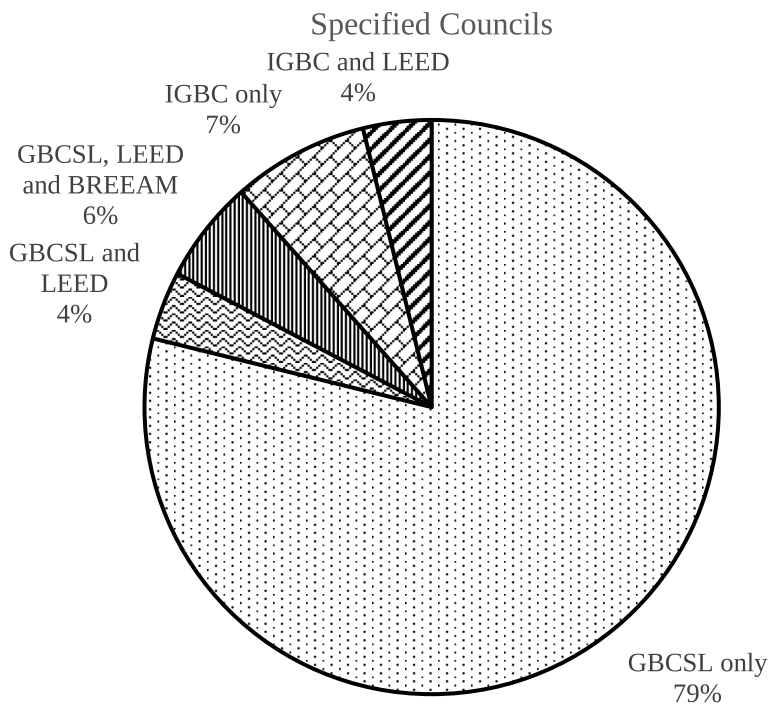

Figure 11: Specified councils of Accredited Professionals

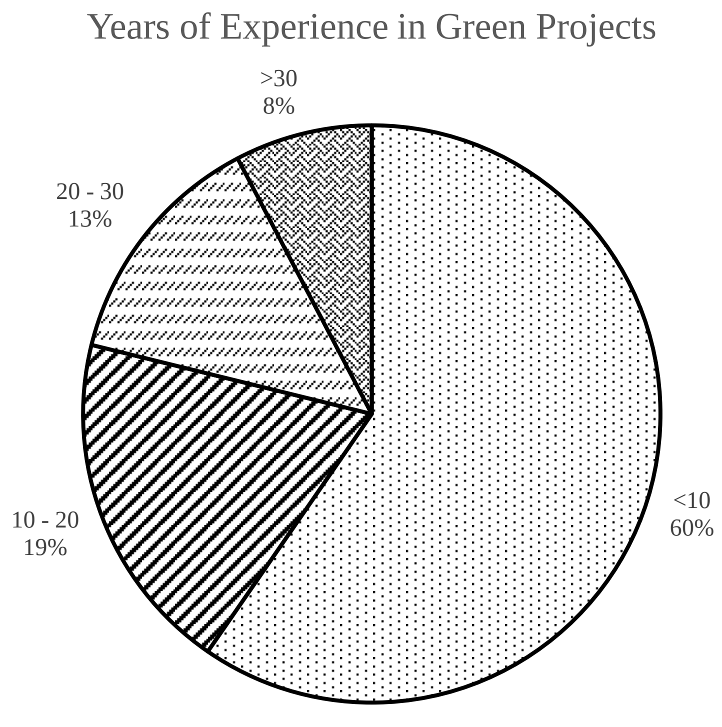

Figure 12: Years of experience in Green Projects of the respondents of Survey 1

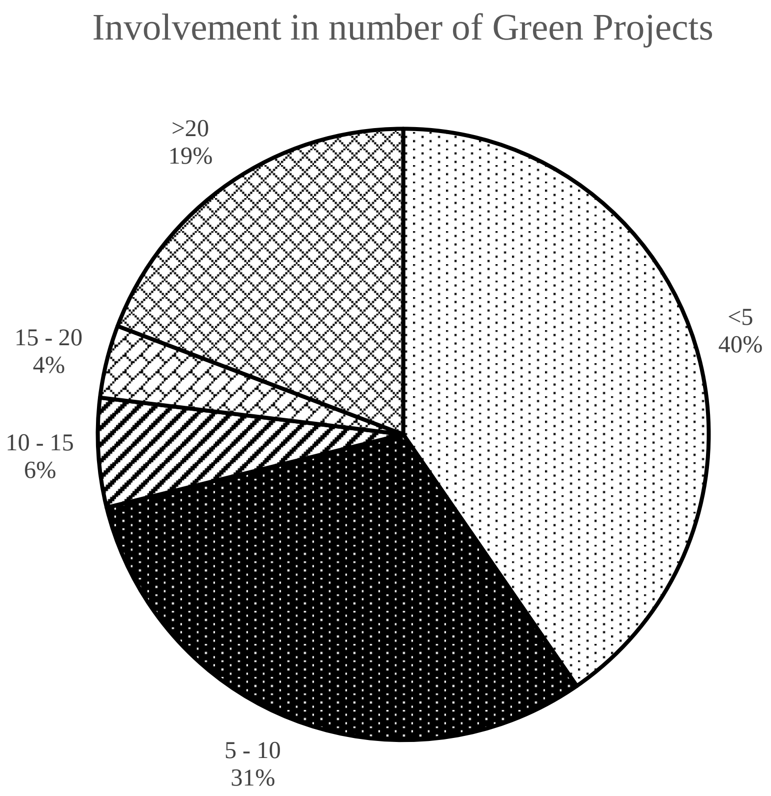

Figure 13: Involvement in number of Green Projects by the respondents of Survey 1

4.1.1 Hierarchy of themes and sub-themes under eco-design

After the pilot survey, additional sub-themes were added to the survey and the survey was modified. The factor "Applicability with the fundamentals" has been suggested to be added to the survey which does not fall under any theme of eco-design. However, since the experts found it to be a very important parameter for material selection, it had been included in the survey on the level of importance of sub-themes. It was identified as a Prerequisite (P) for the material selection framework. The rest of the sub-themes have been classified under the themes such as ecological, economic, social, and cultural and have been summarized in Figure 14. Further, the descriptions of each sub-theme are provided.

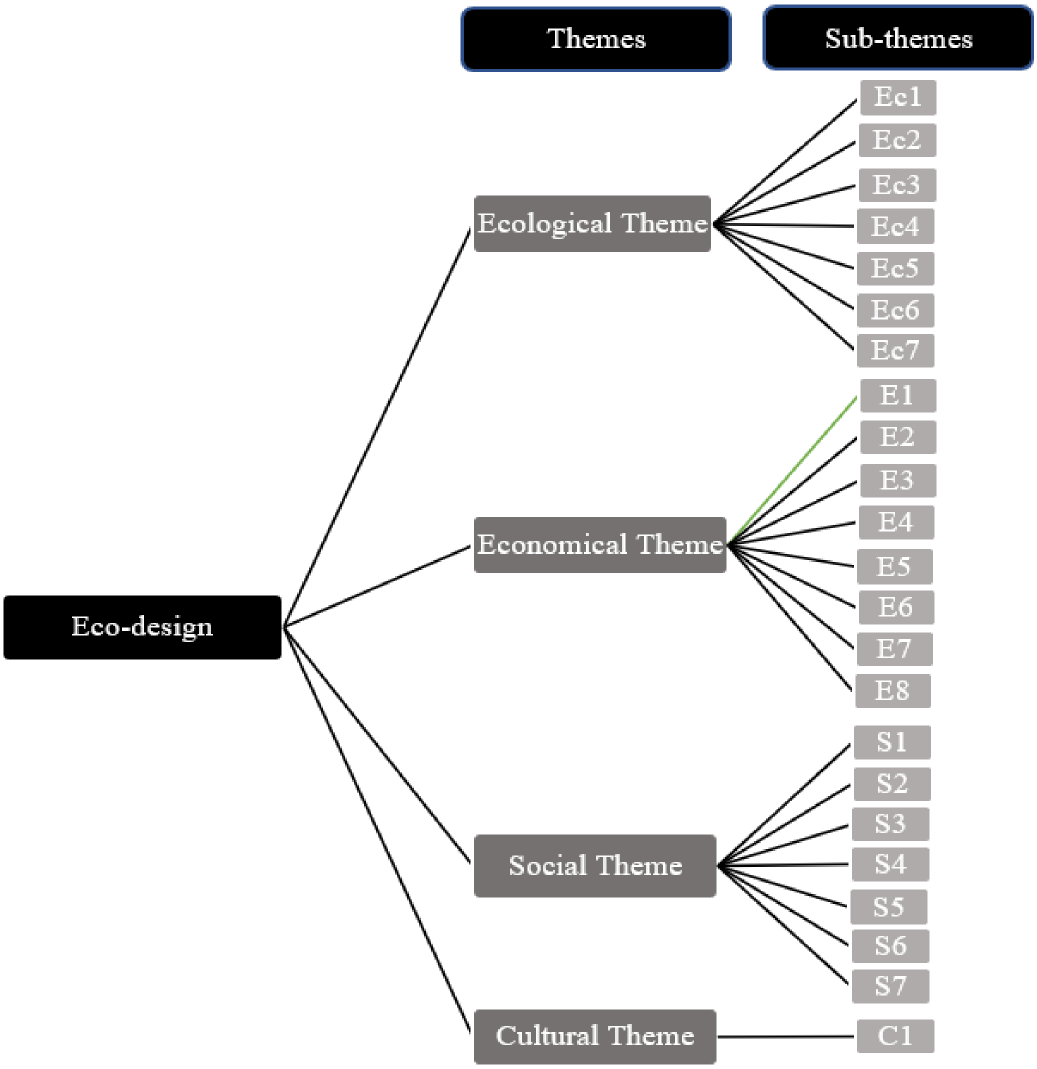

Figure 14: Hierarchy of themes and sub-themes under eco-design

Ec1: Saving energy

- This includes the total energy consumed in the life cycle perspective by embodied as well as operational stages (Dixit et al., 2010; Thevarajah et al., 2020). It emphasizes the quantity of energy used. It is an important criterion emphasized in plenty of research works to be considered under material selection (Abeysundra et al., 2007; Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004; Wen et al., 2020; Zuo & Zhao, 2014).

Ec2: Reducing energy emissions

- This includes the emissions due to embodied as well as operational stages (Thevarajah et al., 2020). It signifies how clean the consumed energy is.

Ec3: Reducing overexploitation of natural resources

- The decline of natural resources has become a serious issue in recent times (Bundgaard et al., 2017). Also, the use of renewable materials is highly encouraged using this theme (Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021; Wen et al., 2020).

Ec4: Reducing waste

- Building construction materials are responsible for generating a lot of waste (O. P. Akadiri, 2011; Gurupatham et al., 2021). Reduced wastage generation, use of waste material in production, and proper disposal of waste are included under this sub-theme (P. O. Akadiri et al., 2013a; Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004; Wen et al., 2020).

Ec5: Reducing Hazardous or toxic content

- This is emphasized in several literature works (P. O. Akadiri et al., 2013a; Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004). It is important to avoid the materials that emit or release toxic substances (Wen et al., 2020)

Ec6: Water efficiency

- Saving water is an important objective under the Sustainable Development Goals (SDG) as well as emphasized under the Green Rating Tools. It includes efficient water usage, rainwater utilization, and protecting water sources (Hossaini et al., 2014; Peuportier et al., 2013; Wen et al., 2020).

Ec7: Reducing the heat island effect

- This has been emphasized under the Green Building Rating Systems. It impacts the microclimate (Wen et al., 2020).

E1: Reducing construction costs and increasing affordability

- The initial construction cost highly impacts the material selection (Abeysundra et al., 2007; Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021). It contributes to around 50 % of the total life cycle costs (N. Wang et al., 2010). Reduction of the initial cost increases the affordability of the product.

E2: Reducing operational costs and cost savings due to energy reduction

- The operational cost impacts the total cost when considering the long run and it is an essential parameter to be considered in material selection (Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Zuo & Zhao, 2014).

E3: Reducing maintenance cost

- The cost of maintenance has been pointed out in past literature works concerning material selection (Peuportier et al., 2013; Sahlol et al., 2021).

E4: Reducing replacement cost and durability consideration

- The use of high-quality materials that are durable for a longer period reduces the cost of replacement (Wen et al., 2020) and it is a factor to be considered in material selection economic wise (P. O. Akadiri et al., 2013a; Lee et al., 2013; Sahlol et al., 2021)

E5: Reducing demolition cost

- Demolition is a stage of a building in its life cycle (Peuportier et al., 2013; Sahlol et al., 2021). It could also contribute to a considerable extent in life cycle costs.

E6: Salvage value

- This is the usable value that remains after the end of demolition. A building material being able to utilize after the end of life of a building is a positive aspect that adds economic value.

E7: Cost saving by reuse and recycling

- Reuse and recycling are also encouraged concerning the economic aspect that can reduce the cost of construction.

E8: Local availability for reducing foreign exchange

- The availability of materials in the local context reduces foreign exchange.

S1: Improving indoor air quality

- Improving indoor air quality is an important aspect considered in construction (Hossaini et al., 2014; Peuportier et al., 2013; Sahlol et al., 2021). Poor air quality leads to “Sick Building Syndrome” which would lead to adverse health effects (O. P. Akadiri, 2011).

S2: Improving thermal comfort

- Thermal comfort is a factor that is considered widely in the literature under comfort conditions (Abeysundra et al., 2007; P. O. Akadiri et al., 2013a; Peuportier et al., 2013; Sahlol et al., 2021; Seo et al., 2004) that can even reduce the operational energy use and the cost due to that (Gurupatham et al., 2021).

S3: Reducing risk and provision of safety

- The risks can include fire, explosion, radiation, and other possible factors while safety is expected as a priority by the occupants (Lambrechts et al., 2019; Peuportier et al., 2013; Sahlol et al., 2021; Zuo & Zhao, 2014).

S4: Reducing noise

- Noise reduction is a comfort criterion present in the literature (Peuportier et al., 2013; Wen et al., 2020). The acoustic performance of the material is given importance through this sub-theme.

S5: Social Acceptance

- Being accepted by society is a concern since the introduction of materials is in vain if their usage is limited.

S6: Aesthetic appearance

- Aesthetic appearance is a factor that could have varying opinions among several occupants (Abeysundra et al., 2007; Peuportier et al., 2013; Sahlol et al., 2021). It is a subjective aspect that could only be concluded based on surveys and opinions.

S7: Local sourcing of raw materials for Improving employment opportunities

- Improving employment is a concern that is included under SDGs as well as other Green Rating tools and past literature (O. P. Akadiri, 2011). Local sourcing is a way to provide job opportunities for the local community.

C1: Conserving local architecture

- It becomes important for materials to be in line with the local architecture considering the culture of a region.

4.1.2 The sample size of respondents

Among the targeted respondents 54 of them replied positively expressing their willingness to participate in the survey. The survey was conducted through interviews with one-to-one interaction via an online platform. Complete responses were collected from 52 respondents. Since the variables are continuous Cochran's sample size calculation for continuous data was used to check the adequacy of the sample size (Kamali & Hewage, 2016; Kotrlik & Higgins, 2001). Accordingly, taking the commonly used confidence level and the margin of error (i.e. 95% and 5% respectively) the required minimum sample size was calculated to be 47 (Kamali & Hewage, 2016; Méda et al., 2014; Olson & Kellogg, 2014). Since 52 complete responses were obtained, the required sample size condition is satisfied.

4.1.3 Reliability Analysis

The internal consistency of the responses was checked by performing a reliability analysis. Accordingly, Cronbach's Alpha was calculated (Kamali & Hewage, 2016). The themes are Ecological aspects, Economic aspects, social aspects, and Cultural aspects whereas the themes such as Ecological aspects, Economic aspects, and social aspects consist of 7, 8, and 7 sub-themes respectively while the cultural theme consists of 1 sub-theme. As a result, the internal consistency considering Ecological aspects, Economic aspects, and social aspects have been calculated individually in addition to the overall Cronbach's Alpha including the whole set of responses. The calculated Cronbach's Alpha values have been tabulated in Table 8. Nunnally (1978) stated that the required minimum value for Cronbach's Alpha is 0.7 (Nunnally & Nunnaly, 1978). Hence, the results of the overall data set as well as individual themes are concluded to be reliable.

Table 8: Cronbach's Alpha of responses

Category	Cronbach's Alpha
Overall	0.932
Ecological theme	0.882
Economical theme	0.856
Social theme	0.869

4.1.4 Level of importance of identified sub-themes

The relative importance of each sub-theme had been quantified with the aid of the Relative Index. Table 9 shows the relative index values, ranking by category, overall ranking and the level of importance of the sub-themes.

Table 9: Level of Importance of sub-themes

	Percentage of Score					Relative Index	Ranking by category	Overall ranking	Importance level
	1	**2**	**3**	**4**	**5**				
Pre-requisite									
P	0.00	0.00	14.89	51.06	34.04	0.84	1	14	H
Ecological sub-themes									
Ec1	0.00	1.92	1.92	17.31	78.85	0.95	1	1	H
Ec2	0.00	1.92	1.92	19.23	76.92	0.94	2	2	H
Ec3	0.00	0.00	3.85	32.69	63.46	0.92	5	5	H
Ec4	0.00	1.92	3.85	26.92	67.31	0.92	5	5	H
Ec5	0.00	0.00	1.92	32.69	65.38	0.93	3	3	H
Ec6	0.00	2.08	2.08	33.33	62.50	0.91	7	8	H
Ec7	0.00	0.00	5.56	22.22	72.22	0.93	3	3	H
Economic sub-theme									
E1	0.00	7.69	11.54	42.31	38.46	0.82	6	17	H
E2	0.00	1.92	1.92	30.77	65.38	0.92	1	5	H
E3	0.00	3.85	15.38	44.23	36.54	0.83	4	15	H
E4	0.00	5.77	15.38	36.54	42.31	0.83	4	15	H
E5	1.92	11.54	28.85	38.46	19.23	0.72	8	24	H - M
E6	1.92	5.77	28.85	44.23	19.23	0.75	7	22	H - M
E7	0.00	4.26	6.38	40.43	48.94	0.87	2	12	H
E8	0.00	15.00	10.00	10.00	65.00	0.85	3	13	H
Social sub-theme									
S1	1.92	0.00	5.77	26.92	65.38	0.91	1	8	H
S2	1.92	1.92	1.92	36.54	57.69	0.89	3	11	H
S3	0.00	1.92	3.85	34.62	59.62	0.90	2	10	H
S4	0.00	3.85	15.38	48.08	32.69	0.82	4	17	H
S5	5.77	7.69	19.23	30.77	36.54	0.77	7	21	H - M

S6	0.00	4.17	29.17	41.67	25.00	0.78	6	20	H - M
S7	7.14	3.57	17.86	17.86	53.57	0.81	5	19	H
Cultural sub-theme									
C1	1.92	5.77	32.69	36.54	23.08	0.75	1	22	H - M

The finalized sub-themes are all either of high importance or high to medium importance. The relative indices of the sub-themes have been interpreted in Figure 15. In addition to overall responses, the responses have been analyzed as a response based on the expertise of respondents, professional discipline, and nationality of the respondents and the results have been presented in Tables 10 to 15 and Figures 16 to 18.

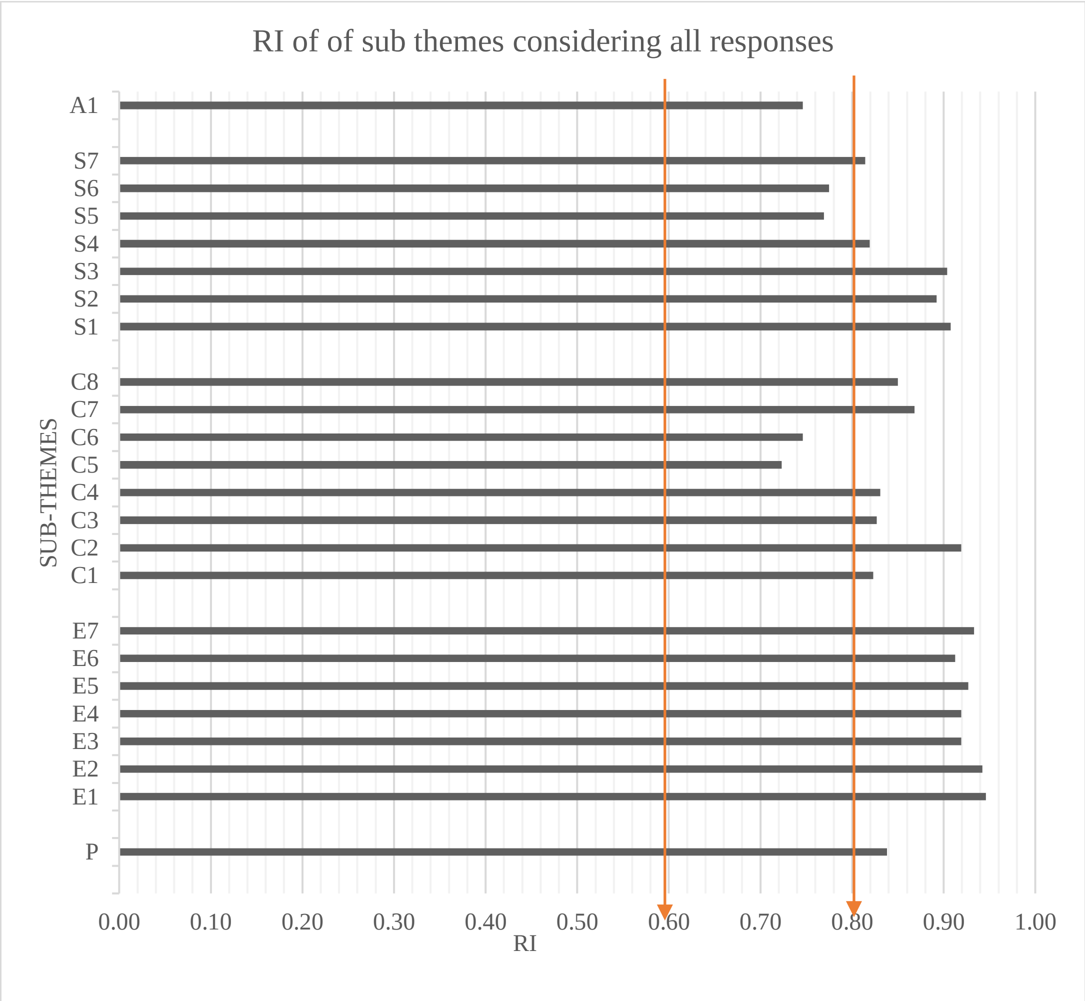

Figure 15: Relative Indices of sub-themes

Table 10: RI of experts with more experience

	Percentage of Score					Relative Index	Importance level
	1	**2**	**3**	**4**	**5**		
P	0.00	0.00	12.50	37.50	50.00	0.88	H
Ec1	0.00	9.09	0.00	0.00	90.91	0.95	H
Ec2	0.00	0.00	9.09	0.00	90.91	0.96	H
Ec3	0.00	0.00	0.00	27.27	72.73	0.95	H
Ec4	0.00	0.00	0.00	27.27	72.73	0.95	H
Ec5	0.00	0.00	0.00	27.27	72.73	0.95	H
Ec6	0.00	0.00	10.00	40.00	50.00	0.88	H
Ec7	0.00	0.00	0.00	0.00	100.00	1.00	H
E1	0.00	18.18	0.00	9.09	72.73	0.87	H
E2	0.00	0.00	9.09	9.09	81.82	0.95	H
E3	0.00	0.00	9.09	54.55	36.36	0.85	H
E4	0.00	0.00	9.09	27.27	63.64	0.91	H
E5	9.09	0.00	36.36	27.27	27.27	0.73	H - M
E6	0.00	9.09	36.36	27.27	27.27	0.75	H - M
E7	0.00	0.00	0.00	44.44	55.56	0.91	H
E8	0.00	0.00	0.00	0.00	100.00	1.00	H
S1	0.00	0.00	9.09	0.00	90.91	0.96	H
S2	0.00	0.00	9.09	45.45	45.45	0.87	H
S3	0.00	0.00	0.00	27.27	72.73	0.95	H
S4	0.00	9.09	9.09	45.45	36.36	0.82	H
S5	9.09	0.00	9.09	18.18	63.64	0.85	H
S6	0.00	0.00	0.00	50.00	50.00	0.90	H
S7	0.00	0.00	0.00	25.00	75.00	0.95	H
C1	0.00	18.18	0.00	45.45	36.36	0.80	H

Table 11: RI of experts with less experience

	Percentage of Score					Relative Index	Importance level
	1	**2**	**3**	**4**	**5**		
P	0.00	0.00	15.38	53.85	30.77	0.83	H
Ec1	0.00	0.00	2.44	21.95	75.61	0.95	H
Ec2	0.00	2.44	0.00	24.39	73.17	0.94	H
Ec3	0.00	0.00	4.88	34.15	60.98	0.91	H
Ec4	0.00	2.44	4.88	26.83	65.85	0.91	H
Ec5	0.00	0.00	2.44	34.15	63.41	0.92	H
Ec6	0.00	2.63	0.00	31.58	65.79	0.92	H
Ec7	0.00	0.00	6.67	26.67	66.67	0.92	H
E1	0.00	4.88	14.63	51.22	29.27	0.81	H
E2	0.00	2.44	0.00	36.59	60.98	0.91	H
E3	0.00	0.00	19.51	53.66	26.83	0.81	H
E4	0.00	7.32	17.07	43.90	31.71	0.80	H
E5	0.00	15.00	35.00	35.00	15.00	0.70	H - M
E6	2.44	7.32	34.15	48.78	7.32	0.70	H - M
E7	0.00	5.26	7.89	39.47	47.37	0.86	H
E8	0.00	17.65	11.76	11.76	58.82	0.82	H
S1	2.44	0.00	4.88	34.15	58.54	0.89	H
S2	2.44	2.44	0.00	34.15	60.98	0.90	H
S3	0.00	2.44	4.88	36.59	56.10	0.89	H
S4	0.00	2.44	17.07	48.78	31.71	0.82	H
S5	4.88	9.76	21.95	34.15	29.27	0.75	H - M
S6	0.00	5.00	35.00	40.00	20.00	0.75	H - M
S7	8.33	4.17	20.83	16.67	50.00	0.79	H - M
C1	2.44	2.44	41.46	34.15	19.51	0.73	H - M

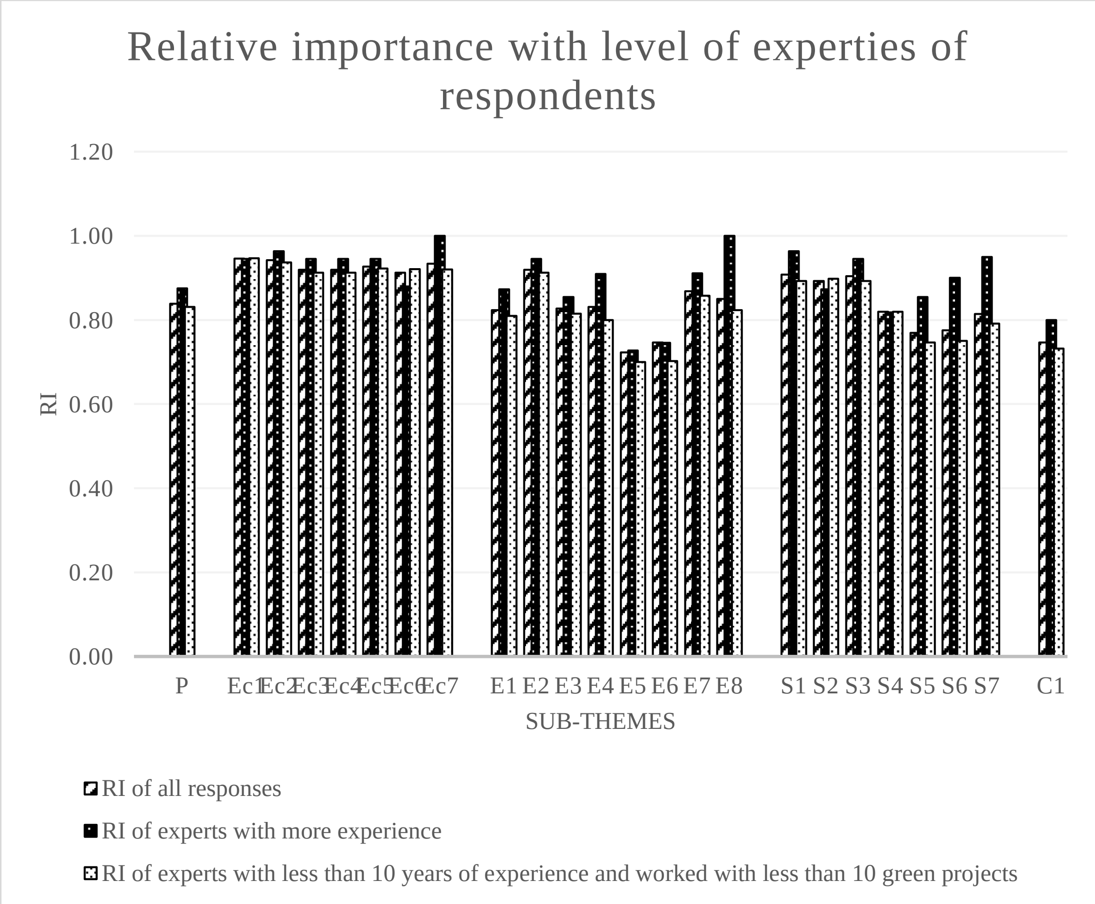

Figure 16: Relative importance with the level of expertise of respondents

21% of the experts interviewed had over 10 years of experience in Green Projects and have worked with more than 10 Green Projects. The respondents with greater than 10 years of experience in Green Projects and who have worked with more than 10 Green Projects are defined as experts with more experience while others are defined as experts with less experience. Analysis based on the level of expertise shows that irrespective of the expertise of the respondents all have rated the sub-themes as of High or High-Medium importance.

Table 12: RI of experts from Engineering discipline

	Percentage of Score					Relative Index	Importance level
	1	**2**	**3**	**4**	**5**		
P	0.00	0.00	12.50	52.50	35.00	0.85	H
Ec1	0.00	2.22	2.22	15.56	80.00	0.95	H
Ec2	0.00	0.00	2.22	20.00	77.78	0.95	H
Ec3	0.00	0.00	2.22	35.56	62.22	0.92	H
Ec4	0.00	2.22	2.22	26.67	68.89	0.92	H
Ec5	0.00	0.00	2.22	33.33	64.44	0.92	H
Ec6	0.00	0.00	2.38	28.57	69.05	0.93	H
Ec7	0.00	0.00	0.00	23.08	76.92	0.95	H
E1	0.00	8.51	10.64	44.68	36.17	0.82	H
E2	0.00	2.22	2.22	28.89	66.67	0.92	H
E3	0.00	4.44	17.78	44.44	33.33	0.81	H
E4	0.00	6.67	15.56	37.78	40.00	0.82	H
E5	2.22	6.67	31.11	40.00	20.00	0.74	H - M
E6	0.00	4.44	33.33	42.22	20.00	0.76	H - M
E7	0.00	0.00	7.50	40.00	52.50	0.89	H
E8	0.00	6.67	6.67	13.33	73.33	0.91	H
S1	0.00	0.00	6.67	24.44	68.89	0.92	H
S2	0.00	2.22	2.22	40.00	55.56	0.90	H
S3	0.00	2.22	4.44	35.56	57.78	0.90	H
S4	0.00	4.44	13.33	46.67	35.56	0.83	H
S5	4.44	8.89	20.00	31.11	35.56	0.77	H - M
S6	0.00	4.88	31.71	41.46	21.95	0.76	H - M
S7	8.33	4.17	20.83	8.33	58.33	0.81	H
C1	0.00	4.44	33.33	40.00	22.22	0.76	H - M

Table 13: RI of experts from Architecture discipline

	Percentage of Score					Relative Index	Importance level
	1	**2**	**3**	**4**	**5**		
P	0.00	0.00	33.33	33.33	33.33	0.80	H
Ec1	0.00	0.00	0.00	33.33	66.67	0.93	H
Ec2	0.00	16.67	0.00	16.67	66.67	0.87	H
Ec3	0.00	0.00	16.67	16.67	66.67	0.90	H
Ec4	0.00	0.00	16.67	33.33	50.00	0.87	H
Ec5	0.00	0.00	0.00	33.33	66.67	0.93	H
Ec6	0.00	20.00	0.00	60.00	20.00	0.76	H
Ec7	0.00	0.00	25.00	25.00	50.00	0.85	H
E1	0.00	0.00	25.00	25.00	50.00	0.85	H
E2	0.00	0.00	0.00	50.00	50.00	0.90	H
E3	0.00	0.00	0.00	50.00	50.00	0.90	H
E4	0.00	0.00	16.67	16.67	66.67	0.90	H
E5	0.00	50.00	16.67	16.67	16.67	0.60	H - M
E6	16.67	16.67	0.00	50.00	16.67	0.67	H - M
E7	0.00	33.33	0.00	50.00	16.67	0.70	H - M
E8	0.00	50.00	25.00	0.00	25.00	0.60	H - M
S1	16.67	0.00	0.00	50.00	33.33	0.77	H - M
S2	16.67	0.00	0.00	16.67	66.67	0.83	H
S3	0.00	0.00	0.00	33.33	66.67	0.93	H
S4	0.00	0.00	33.33	50.00	16.67	0.77	H - M
S5	16.67	0.00	16.67	16.67	50.00	0.77	H - M
S6	0.00	0.00	16.67	33.33	50.00	0.87	H
S7	0.00	0.00	0.00	66.67	33.33	0.87	H
C1	16.67	0.00	33.33	16.67	33.33	0.70	H - M

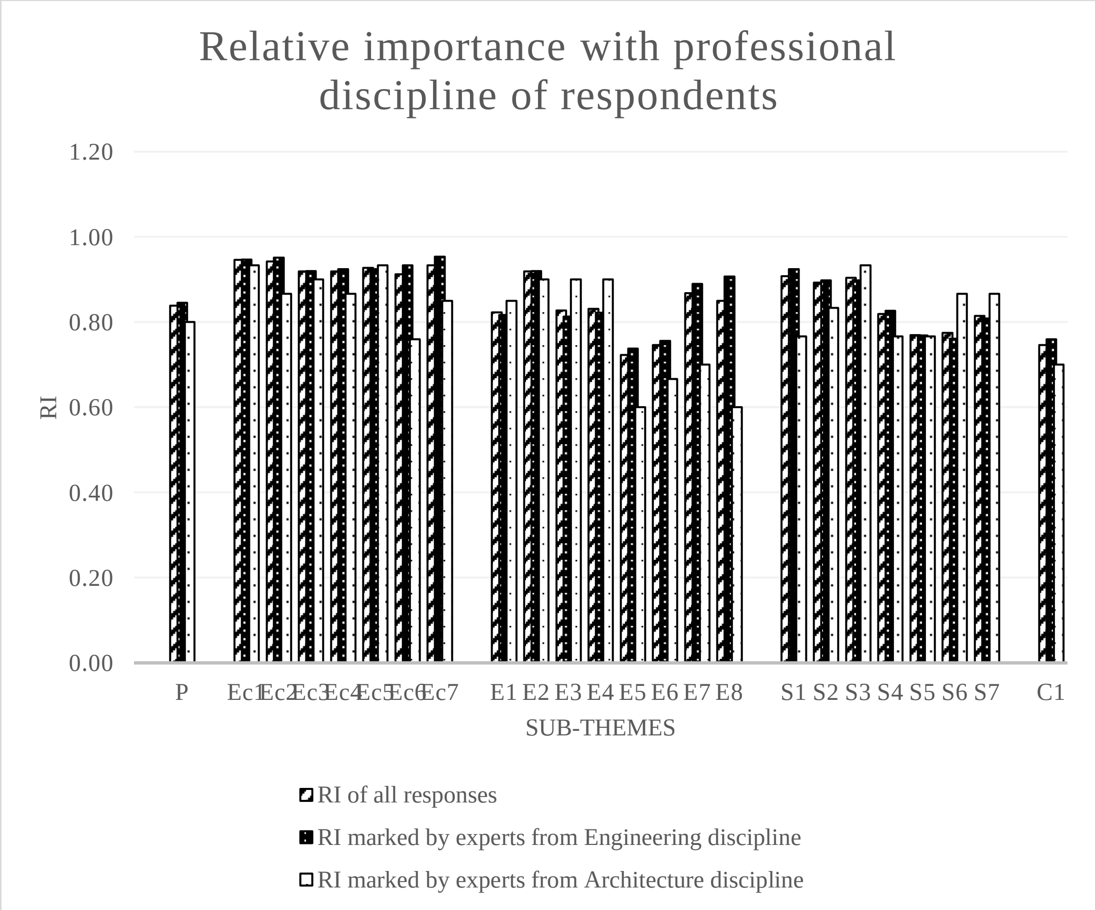

Figure 17: Relative importance with the professional discipline of respondents

98% of the respondents are either from the discipline of engineering or architecture. Only 12% of the respondents are architects while the majority are engineers. Here, the responses are checked by analyzing the responses of engineers and architects separately. Again, all the identified sub-themes are rated as either High or High-Medium importance irrespective of the professional discipline.

Table 14: RI of experts from Sri Lanka

	Percentage of Score					Relative Index	Importance level
	1	**2**	**3**	**4**	**5**		
P	0.00	0.00	17.07	51.22	31.71	0.83	H
Ec1	0.00	2.17	2.17	17.39	78.26	0.94	H
Ec2	0.00	2.17	2.17	17.39	78.26	0.94	H
Ec3	0.00	0.00	4.35	34.78	60.87	0.91	H
Ec4	0.00	2.17	4.35	28.26	65.22	0.91	H
Ec5	0.00	0.00	2.17	32.61	65.22	0.93	H
Ec6	0.00	2.38	2.38	35.71	59.52	0.90	H
Ec7	0.00	0.00	0.00	23.08	76.92	0.95	H
E1	0.00	8.70	10.87	41.30	39.13	0.82	H
E2	0.00	2.17	2.17	26.09	69.57	0.93	H
E3	0.00	4.35	15.22	43.48	36.96	0.83	H
E4	0.00	6.52	17.39	32.61	43.48	0.83	H
E5	2.17	13.04	30.43	36.96	17.39	0.71	H - M
E6	2.17	6.52	30.43	45.65	15.22	0.73	H - M
E7	0.00	4.88	7.32	43.90	43.90	0.85	H
E8	0.00	21.43	7.14	7.14	64.29	0.83	H
S1	2.17	0.00	6.52	28.26	63.04	0.90	H
S2	2.17	2.17	2.17	32.61	60.87	0.90	H
S3	0.00	2.17	4.35	34.78	58.70	0.90	H
S4	0.00	4.35	17.39	47.83	30.43	0.81	H
S5	6.52	8.70	19.57	28.26	36.96	0.76	H - M
S6	0.00	4.76	28.57	38.10	28.57	0.78	H - M
S7	9.09	4.55	22.73	13.64	50.00	0.78	H - M
C1	2.17	6.52	34.78	36.96	19.57	0.73	H - M

Table 15: RI of experts from India

	Percentage of Score					Relative Index	Importance level
	1	**2**	**3**	**4**	**5**		
P	0.00	0.00	0.00	50.00	50.00	0.90	H
Ec1	0.00	0.00	0.00	16.67	83.33	0.97	H
Ec2	0.00	0.00	0.00	33.33	66.67	0.93	H
Ec3	0.00	0.00	0.00	16.67	83.33	0.97	H
Ec4	0.00	0.00	0.00	16.67	83.33	0.97	H
Ec5	0.00	0.00	0.00	33.33	66.67	0.93	H
Ec6	0.00	0.00	0.00	16.67	83.33	0.97	H
Ec7	0.00	0.00	20.00	20.00	60.00	0.88	H
E1	0.00	0.00	16.67	50.00	33.33	0.83	H
E2	0.00	0.00	0.00	66.67	33.33	0.87	H
E3	0.00	0.00	16.67	50.00	33.33	0.83	H
E4	0.00	0.00	16.67	33.33	50.00	0.87	H
E5	0.00	0.00	33.33	33.33	33.33	0.80	H
E6	0.00	0.00	0.00	50.00	50.00	0.90	H
E7	0.00	0.00	0.00	16.67	83.33	0.97	H
E8	0.00	0.00	16.67	16.67	66.67	0.90	H
S1	0.00	0.00	0.00	16.67	83.33	0.97	H
S2	0.00	0.00	0.00	66.67	33.33	0.87	H
S3	0.00	0.00	0.00	33.33	66.67	0.93	H
S4	0.00	0.00	0.00	50.00	50.00	0.90	H
S5	0.00	0.00	16.67	50.00	33.33	0.83	H
S6	0.00	0.00	33.33	66.67	0.00	0.73	H - M
S7	0.00	0.00	0.00	33.33	66.67	0.93	H
C1	0.00	0.00	0.00	50.00	50.00	0.90	H

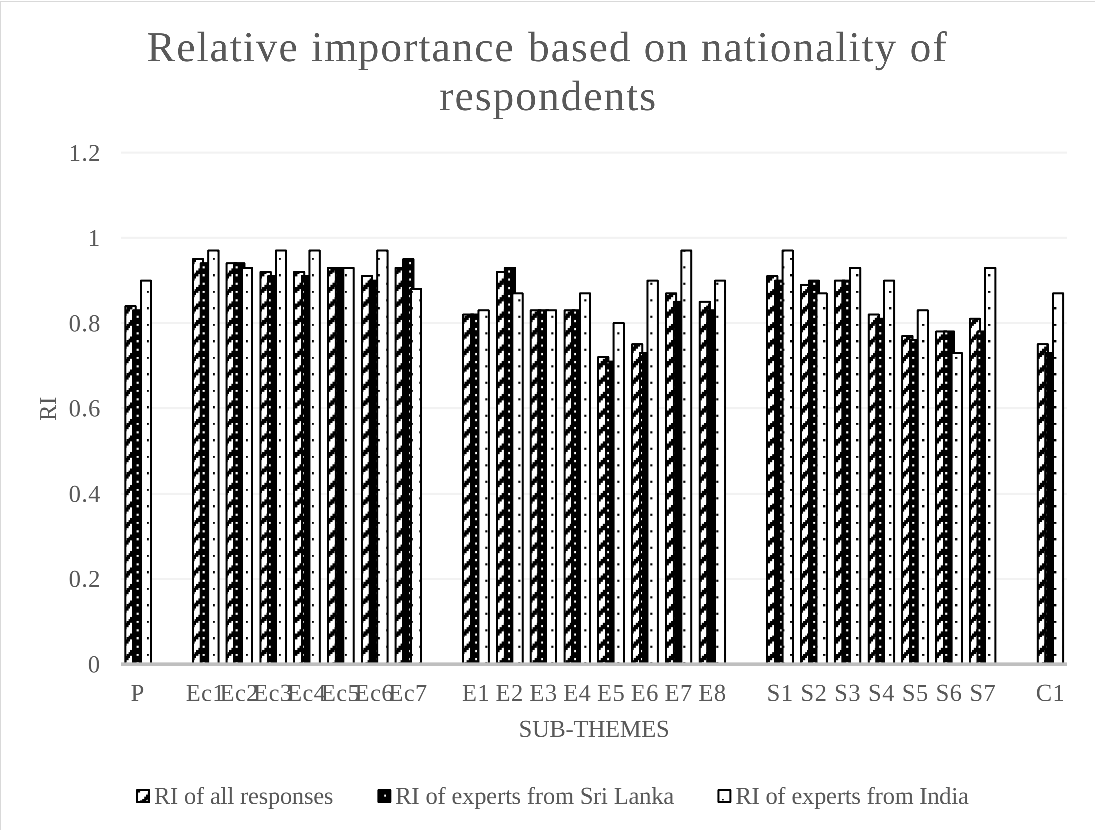

Figure 18: Relative importance based on the nationality of respondents

The majority of the respondents are Sri Lankans and 11% of the respondents are from India. The identified subthemes are all marked to be either High or High-Medium importance irrespective of the nationality of the respondents.

Hence, it could be concluded that irrespective of the level of expertise or the professional discipline or the country they belong the respondents rate the identified sub-themes as of high importance or medium to high level of importance.

4.2 Analysis and results of the Survey on pairwise comparison of themes and sub-themes

A survey on pair-wise comparison was circulated among selective experts in order to introduce weights for the sub-themes. The selection of respondents is elaborated in section 4.2.1 and the analysis of responses is shown in section 4.2.2.

4.2.1 Selection of respondents for the pair-wise comparisons

A group of experts is selected such that they have more years of experience in Green Projects and have been involved with a greater number of Green Projects. Out of the selected participants, the responses were obtained from 8 respondents. It was noticeable that 50% of the respondents had greater than 20 years of experience in green projects and had worked with more than 20 green projects. The 8 respondents provided their support in order to carry out the Delphi technique. The years of experience in green projects and the number of green projects involved by the group of respondents of the pair-wise comparison have been shown in Figures 19 and 20.

4.2.2 Analysis of responses to pair-wise comparisons

The survey on pair-wise comparison had been conducted and each response was analyzed in 4 matrices. Matrix 1 is the comparison of the themes of eco-design. The Matrices 2, 3, and 4 are the pairwise comparison of sub-themes under ecological, economic, and social respectively. Table 16 shows the consistency ratios of responses of each selected respondent (R1 to R8). It was ensured that the Consistency Ratios of each response fall under 0.1. Hence, all 8 responses were aggregated to find out the weights of themes and sub-themes. The judgmental matrices of the aggregated responses of each metric have been shown in Tables 17 to 20 respectively. Further, the local and global weights of themes and sub-themes have been illustrated in Table 21.

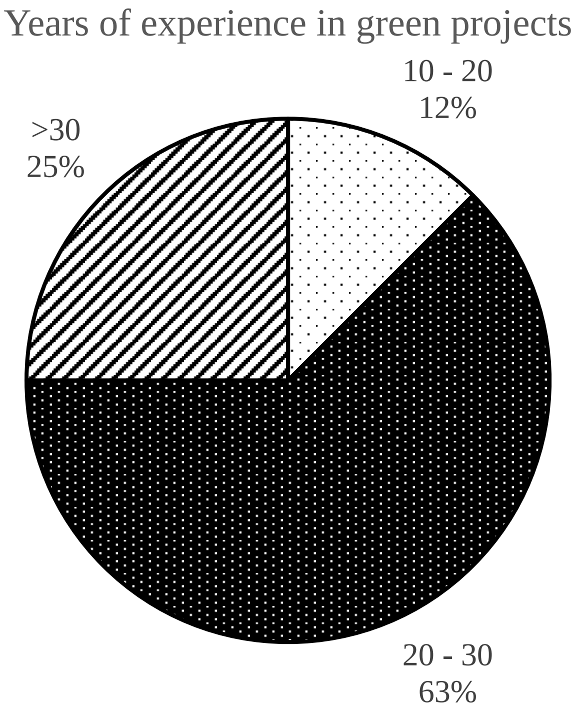

Figure 19: Years of experience in green projects of respondents of survey 2

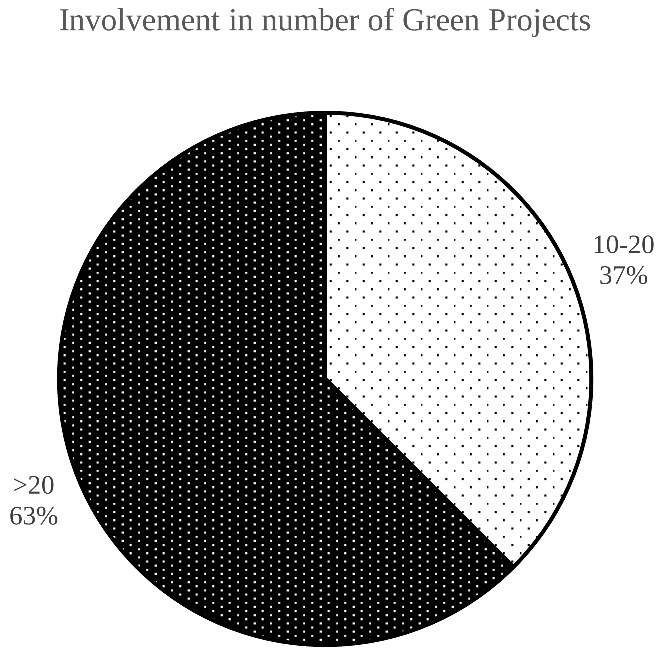

Figure 20: Involvement in number of Green Projects by respondents of survey 2

Table 16: Consistency Ratios of responses of each respondent

Respondent	CR (Matrix 1) 4by4	CR (Matrix 2) 7by7	CR (Matrix 3) 8by8	CR (Matrix 4) 7by7
R1	0.006	0.090	0.074	0.048
R2	0.006	0.081	0.090	0.091
R3	0.008	0.084	0.095	0.084
R4	0.080	0.099	0.099	0.099
R5	0.019	0.091	0.087	0.091
R6	0.068	0.096	0.037	0.062
R7	0.006	0.067	0.084	0.073
R8	0.006	0.016	0.036	0.026

Table 17: Aggregated responses for the themes of Eco-design

	Ecological	Economic	Social	Cultural	Priority vector
Ecological	1	1 3/5	2 5/9	8 1/5	0.4568
Economic	5/8	1	1 5/7	6 2/9	0.3049
Social	2/5	3/5	1	4 1/6	0.1884
Cultural	1/8	1/6	1/4	1	0.0499

CI= 0.0027, RI=0.90, CR= 0.0030

Table 18: Aggregated responses for the ecological sub-themes

	Ec1	Ec2	Ec3	Ec4	Ec5	Ec6	Ec7	Priority vector
Ec1	1	1 4/7	1	2	2	2 2/3	3 3/4	0.2351
Ec2	2/3	1	1	1 3/8	1 2/7	2	3 4/9	0.1718
Ec3	1	1	1	1 4/7	2 4/9	2	2 4/7	0.1994
Ec4	1/2	3/4	2/3	1	1	1 5/8	2	0.1239
Ec5	1/2	7/9	2/5	1	1	1 2/3	2 8/9	0.1248
Ec6	3/8	1/2	1/2	5/8	3/5	1	1 3/4	0.0860
Ec7	1/4	2/7	1/2	1/2	1/3	4/7	1	0.0590

CI= 0.0201, RI=1.32, CR= 0.0152

Table 19: Aggregated responses for the economic sub-themes

	E1	E2	E3	E4	E5	E6	E7	E8	Priority vector
E1	1	1	2 3/8	3	4 4/9	3 7/9	2 3/4	1 3/4	0.2377
E2	1	1	2 1/4	3	3 5/6	4	2 5/9	3	0.2491
E3	3/7	4/9	1	1 1/5	2 1/7	1 6/7	3/5	6/7	0.0994
E4	1/3	1/3	5/6	1	2 1/4	1 1/2	7/9	6/7	0.0892
E5	2/9	1/4	1/2	4/9	1	1	2/3	2/3	0.0560
E6	1/4	1/4	1/2	2/3	1	1	7/9	2/3	0.0634
E7	3/8	2/5	1 2/3	1 2/7	1 1/2	1 2/7	1	1 1/2	0.1090
E8	4/7	1/3	1 1/6	1 1/6	1 3/7	1 3/7	2/3	1	0.0962

CI= 0.0148, RI=1.41, CR= 0.0105

Table 20: Aggregated responses for the social sub-themes

	S1	S2	S3	S4	S5	S6	S7	Priority vector
S1	1	1	1 2/5	1 1/2	3	2 4/9	1 8/9	0.2120
S2	1	1	1	2	2 4/7	2 4/5	1 1/2	0.2003
S3	5/7	1	1	3 1/8	3 1/5	2 5/7	2	0.2171
S4	2/3	1/2	1/3	1	8/9	1 2/5	1 2/7	0.1022
S5	1/3	2/5	1/3	1 1/8	1	1 2/9	1 2/5	0.0916
S6	2/5	1/3	3/8	5/7	4/5	1	1 2/3	0.0869
S7	1/2	2/3	1/2	7/9	5/7	3/5	1	0.0899

CI= 0.0240, RI=1.32, CR= 0.0257

Table 21: Local and Global weights of themes and sub-themes

Theme	Local weight (1)	Sub-theme	Local weight (2)	Global weight (3)
Ecological	0.4568	Saving energy (Ec1)	0.2351	0.1074
		Reducing energy emissions (Ec2)	0.1718	0.0785
		Reducing overexploitation of natural resources (Ec3)	0.1994	0.0911
		Reducing waste (Ec4)	0.1239	0.0566
		Reducing Hazardous or toxic content (Ec5)	0.1248	0.0570
		Water efficiency (Ec6)	0.0860	0.0393
		Reducing heat island effect (Ec7)	0.0590	0.0269
Economic	0.3049	Reducing construction costs and increasing affordability (E1)	0.2377	0.0725
		Reducing operational cost and cost savings due to energy reduction (E2)	0.2491	0.0760
		Reducing maintenance cost (E3)	0.0994	0.0303
		Reducing replacement cost and durability (E4)	0.0892	0.0272
		Reducing demolition cost (E5)	0.0560	0.0171
		Salvage value (E6)	0.0634	0.0193
		Cost saving by reuse and recycling (E7)	0.1090	0.0332
		Local availability for reducing foreign exchange (E8)	0.0962	0.0293
Social	0.1884	Improving indoor air quality (S1)	0.2120	0.0399
		Improving thermal comfort (S2)	0.2003	0.0377
		Reducing risk and provision of safety (S3)	0.2171	0.0409
		Reducing noise (S4)	0.1022	0.0193
		Social Acceptance (S5)	0.0916	0.0172
		Aesthetic appearance (S6)	0.0869	0.0164
		Local sourcing of raw materials for Improving employment opportunities (S7)	0.0899	0.0169
Cultural	0.0499	Conserving local architecture (C1)	1.0000	0.0499

The impact of each eco-design theme and sub-theme has been analyzed using the survey responses. Accordingly, it is evident that the ecological theme creates the highest impact of around 46% and the cultural theme contributes to a lower percentage of around 5% while the economic and social themes impact 30% and 19% respectively. Among the ecological sub-themes, saving energy impacts the highest (11%) followed by reducing overexploitation of natural resources (9%) and then reducing energy emissions (8%). Reducing waste and reducing hazardous or toxic content impacts considerably (6%) while water efficiency and heat island effect contributed to lower percentages like 4% and 3% respectively. Among the economical sub-themes, operational cost reduction impacts the highest (8%) followed by reducing construction cost (7%). Reducing demolition cost and salvage value impact lesser to about 2% while other economical sub-themes weigh around 3%. The social sub-themes create a lower weight comparatively. Sub-themes such as Improving indoor air quality, improving thermal comfort, and reducing risk and provision of safety impact around 4% while the other social sub-themes impact around 2%. While conserving local architecture is identified as the only cultural sub-theme impact with around 5% as same as the weight created by the cultural theme.

Then fuzzy numbers have been applied to the above responses to account for uncertainty. The judgmental matrices of the aggregated responses of each metric when fuzzy numbers are used have been shown in Tables 22 to 25 respectively. Also, the respective local and global weights of themes and sub-themes have been illustrated in Table 26. Since the results do not show higher variation when fuzzy is applied, it is concluded that there is a lower amount of uncertainty associated.

Table 22: Aggregated fuzzy responses for the themes of Eco-design

	Ecological	Economic	Social	Cultural	Priority vector
Ecological	1,1,1	3/2,8/5,25/9	5/3,23/9,11/3	36/5,41/5,35/4	0.4688
Economic	1/3,5/8,2/3	1,1,1	1,12/5,5/2	5,56/9,57/8	0.2893
Social	2/7,2/5,5/8	2/5,3/5,1	1,1,1	25/8,25/6,47/9	0.1925
Cultural	1/9,1/8,1/7	1/7,1/6,1/5	1/5,1/4,1/3	1,1,1	0.0493

CI= 0.0027, RI=0.90, CR= 0.0030

Table 23: Aggregated fuzzy responses for the ecological sub-themes

	Ec1	Ec2	Ec3	Ec4	Ec5	Ec6	Ec7	Priority vector
Ec1	1,1,1	6/5,11/4,21/8	7/9,1,5/3	3/2,2,3	3/2,2,17/6	7/4,8/3,15/4	3,15/4,44/9	0.2420
Ec2	3/8,2/3,5/6	1,1,1	5/7,1,7/4	1,11/8,7/3	1,16/7,2	7/4,2,29/9	8/3,31/9,33/7	0.1799
Ec3	3/5,1,9/7	4/7,1,11/8	1,1,1	5/4,11/4,22/9	13/6,22/9,32/9	11/,2,16/5	12/7,18/7,11/3	0.1976
Ec4	2/7,4/9,1/2	3/7,3/4,1	2/5,2/3,4/5	1,1,1	¾,1,5/3	1,13/8,8/3	7/5,2,19/6	0.1203
Ec5	1/3,4/9,1/2	1/2,7/9,1	2/7,2/5,1/2	3/5,1,11/8	1,1,1	4/3,5/3,13/5	2,26/9,4	0.1201
Ec6	1/4,3/8,4/7	1/3,1/2,4/7	1/3,1/2,2/3	3/8,5/8,1	2/5,3/5,3/4	1,1,1	6/5,7/4,11/4	0.0834
Ec7	1/5,1/4,1/3	2/9,2/7,3/8	1/3,1/2,5/7	1/3,1/2,5/7	¼,1/3,1/2	3/8,4/7,5/6	1,1,1	0.0568

CI= 0.0201, RI=1.32, CR= 0.0152

Table 24: Aggregated fuzzy responses for the economic sub-themes

	E1	E2	E3	E4	E5	E6	E7	E1	Priority vector
E1	1,1,1	4/5,1,3/2	5/3,19/8,7/2	13/6,3,37/9	10/3,40/9,11/2	23/7,34/9,5	7/3,11/4,4	4/3,7/4,11/4	0.2446
E2	5/7,1,11/8	1,1,1	9/5,9/4,17/5	15/7,3,37/9	3,23/2,5	22/7,4,22/7	2,23/9,19/5	7/3,3,29/7	0.2527
E3	2/7,3/7,3/5	2/7,4/9,5/9	1,1,1	¾,6/5,2	7/5,15/7,19/6	1,13/7,8/3	2/5,3/5,1	5/9,6/7,10/7	0.0967
E4	¼,1/3,1/2,	¼,1/3,1/2	½,5/6,11/4	1,1,1	7/5,9/4,23/7	1,3/2,5/2	3/5,7/9,5/4	2/3,6/7,11/8	0.0914
E5	1/6,2/9,1/3	1/5,1/4,1/3	1/3,1/2,1	1/3,4/9,5/7	1,1,1	4/5,1,8/3	½,2/3,11/9	½,2/3,1	0.0590
E6	1/5,1/4,1/3	1/5,1/4,1/3	3/8,1/2,1	2/5,2/3,1	3/5,1,20/9	1,1,1	4/7,7/9,9/7	½,2/3,10/9	0.0621
E7	¼,3/8,3/7	¼,2/5,1/2	1,5/3,12/5	4/5,9/7,13/8	5/6,3/2,2	7/9,9/7,12/7	1,1,1	5/4,3/2,21/8	0.1018
E8	2/5,4/7,4/5	¼,1/31/2	2/3,7/6,16/9	¾,7/6,13/9	1,11/7,9/4	1,10/7,2	3/8,2/3,4/5	1,1,1	0.0917

CI= 0.0148, RI=1.41, CR= 0.0105

Table 25: Aggregated responses for the social sub-themes

	S1	S2	S3	S4	S5	S6	S7	Priority vector
S1	1,1,1	7/8,1,2	1,7/5,13/6	1,3/2,12/5	7/3,3,4	13/8,22/9,7/2	11/7,17/9,3	0.2217
S2	½,1,8/7	1,1,1	4/5,1,12/5	3/2,2,21/8	2,18/7,17/5	2,14/5,4	11/9,3/2,7/3	0.2016
S3	½,5/7,1	3/5,1,20/9	1,1,1	7/3,25/8,38/9	12/5,16/5,13/3	11/6,19/7,27/7	13/9,2,3	0.2147
S4	2/5,2/3,1	1/3,1/2,2/3	¼,1/3,1/2	1,1,1	5/7,8/9,5/3	1,7/5,12/5	1,9/7,2	0.1047
S5	¼,1/3,3/7	2/7,2/5,1/2	¼,1/3,2/5	3/5,9/8,11/8	1,1,1	6/5,11/9,16/7	1,7/5,22/9	0.0916
S6	2/7,2/5,5/8	¼,1/3,1/2	¼,1/3,1/2	3/7,5/7,1	3/7,4/5,5/6	1,1,1	6/5,5/3,5/2	0.0827
S7	1/3,1/2,2/3	3/7,2/3,5/6	3/7,2/3,5/6	½,7/9,1	2/5,5/7,1	2/5,3/5,5/6	1,1,1	0.0829

CI= 0.0240, RI=1.32, CR= 0.0257

Table 26: Local and Global weights of themes and sub-themes

Theme	Local weight (1)	Sub-theme	Local weight (2)	Global weight (3)
Ecological	0.4688	Saving energy (Ec1)	0.2420	0.1134
		Reducing energy emissions (Ec2)	0.1799	0.0843
		Reducing overexploitation of natural resources (Ec3)	0.1976	0.0926
		Reducing waste (Ec4)	0.1203	0.0564
		Reducing Hazardous or toxic content (Ec5)	0.1201	0.0563
		Water efficiency (Ec6)	0.0834	0.0391
		Reducing heat island effect (Ec7)	0.0568	0.0266
Economic	0.2893	Reducing construction costs and increasing affordability (E1)	0.2446	0.0707
		Reducing operational cost and cost savings due to energy reduction (E2)	0.2527	0.0731
		Reducing maintenance cost (E3)	0.0967	0.0280
		Reducing replacement cost and durability (E4)	0.0914	0.0264
		Reducing demolition cost (E5)	0.0590	0.0171
		Salvage value (E6)	0.0621	0.0180
		Cost saving by reuse and recycling (E7)	0.1018	0.0294
		Local availability for reducing foreign exchange (E8)	0.0917	0.0265
Social	0.1925	Improving indoor air quality (S1)	0.2217	0.0427
		Improving thermal comfort (S2)	0.2016	0.0388
		Reducing risk and provision of safety (S3)	0.2147	0.0413
		Reducing noise (S4)	0.1047	0.0202
		Social Acceptance (S5)	0.0916	0.0176
		Aesthetic appearance (S6)	0.0827	0.0159
		Local sourcing of raw materials for Improving employment opportunities (S7)	0.0829	0.0160
Cultural	0.0493	Conserving local architecture (C1)	1.0000	0.0493

4.3 Application of the developed framework in comparing materials

The framework was applied to a case study. Tables 27 and 28 show the quantified values with the case study model house and the performance criteria concluded through discussions with the subject matter professionals. The scores denoted in Table 30 follow the Likert scale provided in Table 7.

Then the TOPSIS methodology has been followed to get the performance Score of each alternative for ranking. The normalized weighted values, the Ideal best and the Ideal worst of each sub-theme are shown in Table 29 and Table 30 while the performance score and the ranking of the alternatives have been interpreted in Table 31.

Table 27: Parameters quantified with the aid of case study model house

Sub-theme	Ec1	Ec2	E1	E2	E3	S2
Quantified parameter	Total energy consumed during the building life (MJ)	Total energy emissions during the building life (kgCO2e)	Initial construction cost (SLR)	Operational cost per year (SLR)	Maintenance cost per year (SLR)	Cooling load for comfort criteria per year (KWh)
Units	MJ	$kgCO2_e$	SLR	SLR	SLR	KWh
BCB	1380720	242430	912000	223840	76000	4496
CSB	1360280	257700	620000	256570	76000	5219
CSEB	1236880	230170	680000	223570	76000	4489

Source: (Gurupatham et al., 2021)

Table 28: Parameters quantified through discussions

Sub-theme	Ec3	Ec4	Ec5	Ec6	Ec7	E4	E5	E6	E7	E8	S1	S3	S4	S5	S6	S7	C1
BCB	3	3	4	2	4	4	3	3	3	5	4	3	4	5	4	4	4
CSB	3	3	3	3	2	3	3	3	2	3	3	4	3	4	2	3	3
CSEB	4	4	4	4	4	4	4	2	3	4	4	3	3	3	4	4	3

Table 29: The normalized weighted values of alternatives for each sub-theme

Sub-theme	Quantified parameters			Normalized value	Normalized vector		
	BCB	CSB	CSEB		BCB	CSB	CSEB
Ec1	1380720	1360280	1236880	2299265	0.601	0.592	0.538
Ec2	242430	257700	230170	422090	0.574	0.611	0.545
Ec3	3	3	4	5.83	0.514	0.514	0.686
Ec4	3	3	4	5.83	0.514	0.514	0.686
Ec5	4	3	4	6.40	0.625	0.469	0.625
Ec6	2	3	4	5.39	0.371	0.557	0.743
Ec7	4	2	4	6.00	0.667	0.333	0.667
E1	912000	620000	680000	1295586	0.704	0.479	0.525
E2	223840	256570	223570	407328	0.550	0.630	0.549
E3	76000	76000	76000	131636	0.577	0.577	0.577
E4	4	3	4	6.40	0.625	0.469	0.625
E5	3	3	4	5.83	0.514	0.514	0.686
E6	3	3	2	4.69	0.640	0.640	0.426
E7	3	2	3	4.69	0.640	0.426	0.640
E8	5	3	4	7.07	0.707	0.424	0.566
S1	4	3	4	6.40	0.625	0.469	0.625
S2	4496	5219	4489	8222	0.547	0.635	0.546
S3	3	4	3	5.83	0.514	0.686	0.514
S4	4	3	3	5.83	0.686	0.514	0.514
S5	5	4	3	7.07	0.707	0.566	0.424
S6	4	2	4	6.00	0.667	0.333	0.667
S7	4	3	4	6.40	0.625	0.469	0.625
C1	4	3	3	5.83	0.686	0.514	0.514

Table 30: The Ideal best and the Ideal worst of each sub-theme

Sub-theme	Weights of Sub-themes	Normalized Weighted Values			Ideal best	Ideal worst
		BCB	CSB	CSEB		
Ec1	0.11	0.064	0.064	0.058	0.058	0.064
Ec2	0.08	0.045	0.048	0.043	0.043	0.048
Ec3	0.09	0.047	0.047	0.062	0.062	0.047
Ec4	0.06	0.029	0.029	0.039	0.039	0.029
Ec5	0.06	0.036	0.027	0.036	0.036	0.027
Ec6	0.04	0.015	0.022	0.029	0.029	0.015
Ec7	0.03	0.018	0.009	0.018	0.018	0.009
E1	0.07	0.051	0.035	0.038	0.035	0.051
E2	0.08	0.042	0.048	0.042	0.042	0.048
E3	0.03	0.017	0.017	0.017	0.017	0.017
E4	0.03	0.017	0.013	0.017	0.017	0.013
E5	0.02	0.009	0.009	0.012	0.012	0.009
E6	0.02	0.012	0.012	0.008	0.012	0.008
E7	0.03	0.021	0.014	0.021	0.021	0.014
E8	0.03	0.021	0.012	0.017	0.021	0.012
S1	0.04	0.025	0.019	0.025	0.025	0.019
S2	0.04	0.021	0.024	0.021	0.021	0.024
S3	0.04	0.021	0.028	0.021	0.028	0.021
S4	0.02	0.013	0.010	0.010	0.013	0.010
S5	0.02	0.012	0.010	0.007	0.012	0.007
S6	0.02	0.011	0.005	0.011	0.011	0.005
S7	0.02	0.011	0.008	0.011	0.011	0.008
C1	0.05	0.034	0.026	0.026	0.034	0.026

Table 31: Performance score and ranking of alternatives

Alternatives	Distance from positive Ideal Solution	Distance from Negative Ideal Solution	Performance Score	Rank
BCB	0.00093	0.0006	0.374	2
CSB	0.00097	0.0004	0.288	3
CSEB	0.0002	0.0012	0.853	1

Accordingly, CSEB material has been ranked to be the best material out of the compared alternatives under the eco-design concept while CSB is ranked to be the worst material. Also, the materials are analyzed under different scenarios using TOPSIS and the results are provided in Figure 21 and Table 32. The considered different scenarios are provided in Table 33.

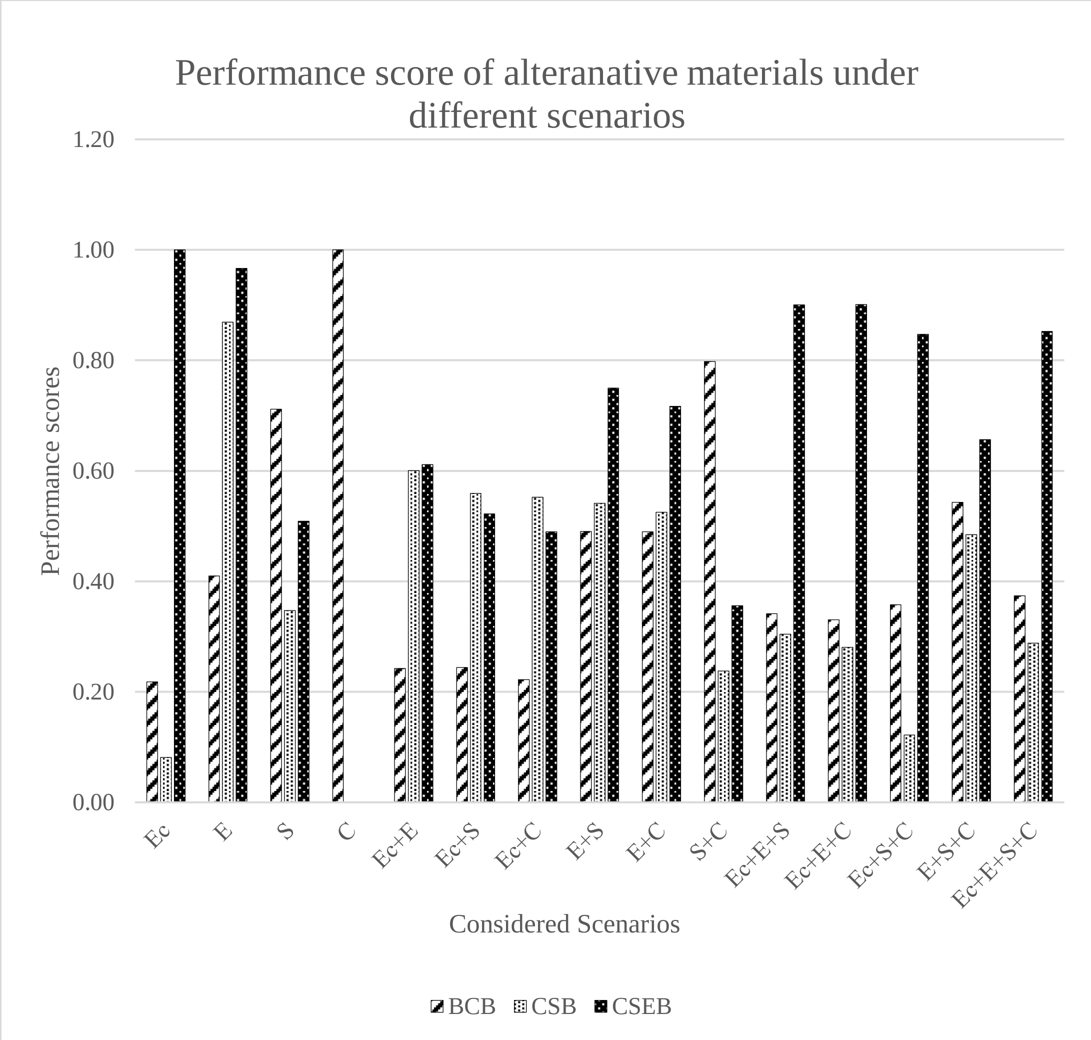

Figure 21: Performance score of alternatives under different scenarios

Table 32: Ranks of alternatives under different scenarios

Scenarios		Ec	E	S	C	Ec+E	Ec+S	Ec+C	E+S	E+C	S+C	Ec+E+S	Ec+E+C	Ec+S+C	E+S+C	Ec+E+S+C
Rank	BCB	2	3	1	1	3	3	3	3	3	1	2	2	2	2	2
	CSB	3	2	3	2	2	1	1	2	2	3	3	3	3	3	3
	CSEB	1	1	2	2	1	2	2	1	1	2	1	1	1	1	1

Table 33: Descriptions of the considered scenarios for the analysis

Scenarios	Descriptions
Ec	Considering ecological theme only
E	Considering economic theme only
S	Considering social theme only
C	Considering cultural theme only
Ec+E	Considering ecological and economic themes
Ec+S	Considering ecological and social themes
Ec+C	Considering ecological and cultural themes
E+S	Considering economic and social themes
E+C	Considering economic and cultural themes
S+C	Considering social and cultural themes
Ec+E+S	Considering ecological, economic, and social themes
Ec+E+C	Considering ecological, economic, and cultural themes
Ec+S+C	Considering ecological, social, and cultural themes
E+S+C	Considering economic, social, and cultural themes
Ec+E+S+C	Considering all four themes of eco-design

CSEB is concluded to be the best material when the alternatives are ranked concerning ecological and economic themes. BCB comes with the best material under social and cultural considerations. However, Since the ecological and economic themes are creating a much greater impact on material selection CSEB is identified to be the best material with overall eco-design aspects.

The application is based on the samples collected from Sri Lanka and India. Further, expanding the scope to various countries and comparing several alternative building materials that are in practice would lead to a full spectrum of construction materials and selection with the aid of the eco-design concept.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The selection of materials needs to consider multiple perspectives in order to identify the most affordable, environmental-friendly, socially-accepted, and culture-centric materials and building systems for communities. Eco-design is a Holistic concept that is categorized under themes such as ecological, economic, social, and cultural where the impact on the material selection is highest by economical and lowest by cultural. The economical sub-theme "saving energy" impacts the highest weight while other sub-themes like reducing overexploitation of natural resources and reducing energy emissions impact considerably. Out of the economical sub-themes, reducing operational energy costs as well as reducing initial construction cost impacts more.

The proposed framework could be highly beneficial for material selection with the aid of eco-design which is a tool for sustainability. However, it is limited to residential buildings and tropical climatic conditions. In order to use the above framework, the beneficiary should be able to quantify or collect the quantified values that indicate the performance of the compared alternative materials with respect to each considered sub-theme. Calculations, Energy modeling, Expert opinions, or any other data collection methods could be used for quantifying the sub-themes.

Further, the comparison of the eco-design-based performance of CSEB with conventional materials like BCB and CSB shows that CSEB is performing very well and CSB is ranked to be the worst among the considered alternatives.

The MCDM methods used in proposing weights and validating the framework have contains drawbacks such as a lack of consideration of uncertainty and ambiguity present in deciding the priorities of different attributes. Also, since a discrete scale is applied it may not be accurate to interpret human interpretations. Fuzzy numbers could be used to rectify the above drawback and the results could be further improved.

5.2 Recommendations

The developed framework is recommended to be utilized for comparing and selecting sustainable building materials out of available alternatives. The developed framework is shown in Table 34 and Figure 22. The outcome of the research work is an Excel file that shows the ranks of considered alternatives when the quantified values of the parameters are entered. Figure 23 shows how the alternatives such as Burnt Clay Bricks (BSB). Cement Sand Blocks (CSB) and Cement Stabilised Earth Blocks (CSEB) are compared and ranked in the Excel form of the framework and Figure 24 shows the Excel form of the developed framework.

Table 34: Framework for material selection with the aid of Eco-design

Theme	Sub-theme	Proposed weights
Ecological Theme (45.7%)	Saving energy	10.7%
	Reducing energy emissions	7.9%
	Reducing overexploitation of natural resources	9.1%
	Reducing waste	5.7%
	Reducing Hazardous or toxic content	5.7%
	Water efficiency	3.9%
	Reducing heat island effect	2.7%
Economic Theme (30.4%)	Reducing construction costs and increasing affordability	7.3%
	Reducing operational cost and cost savings due to energy reduction	7.6%
	Reducing maintenance cost	3.0%
	Reducing replacement cost and durability consideration	2.7%
	Reducing demolition cost	1.7%
	Salvage value	1.9%
	Cost saving by reuse and recycling	3.3%
	Local availability for reducing foreign exchange	2.9%
Social Theme (18.9%)	Improving indoor air quality	4.0%
	Improving thermal comfort	3.8%
	Reducing risk and provision of safety	4.1%
	Reducing noise	1.9%
	Social Acceptance	1.7%
	Aesthetic appearance	1.7%
	Local sourcing of raw materials for Improving employment opportunities	1.7%
Cultural Theme (5.0%)	Conserving local architecture	5.0%

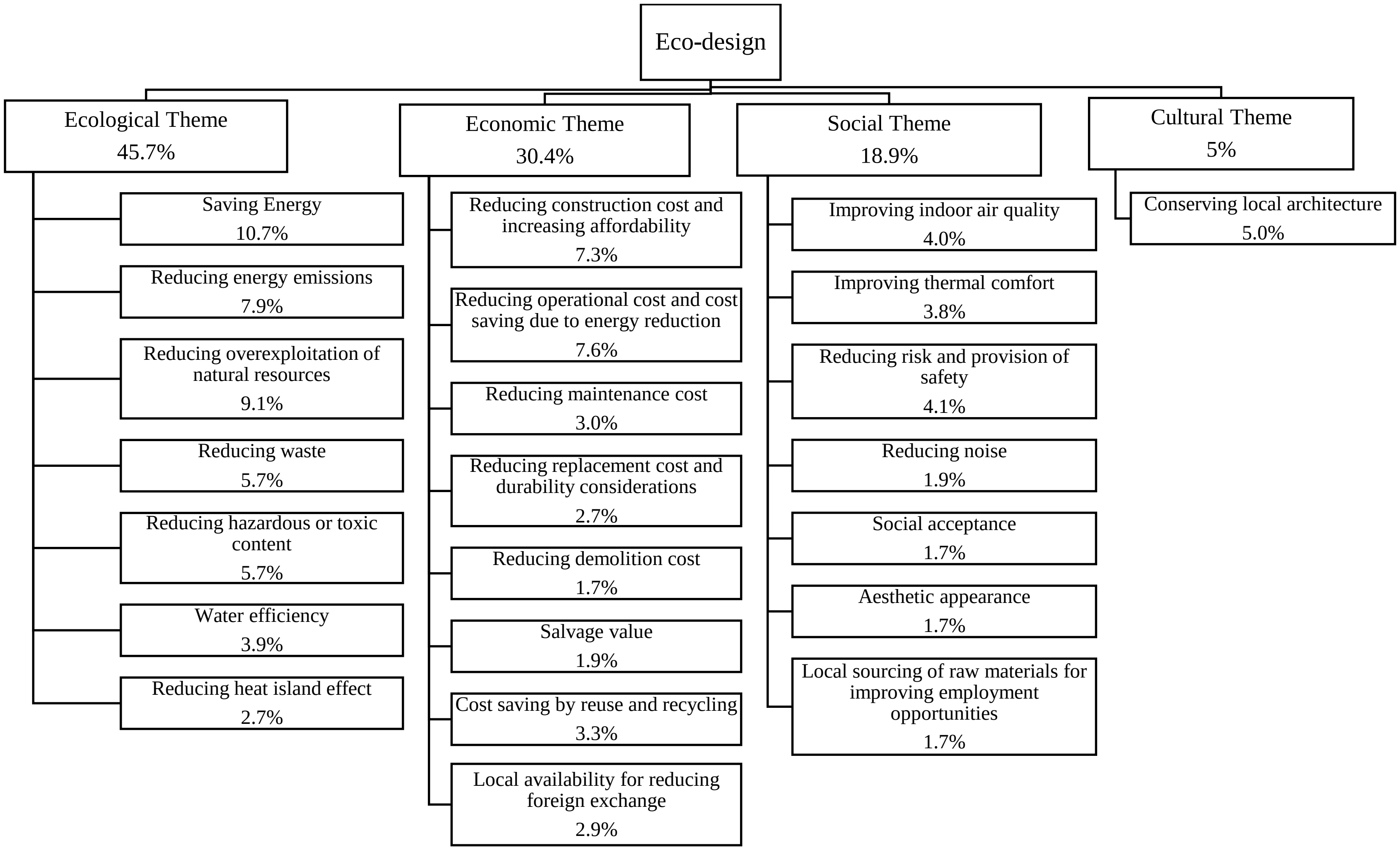

Figure 22: Diagrammatic representation of the developed material selection framework

	Saving energy	Reducing energy emissions	Reducing overexploitation of natural resources	Reducing waste	Reducing Hazardous or toxic content	Water efficiency	Reducing heat island effect	Reducing construction cost and increasing affordability	Reducing operational cost and cost saving due to energy reduction	Reducing maintenance cost	Reducing replacement cost and durability consideration	Reducing demolition cost	Salvage value	Cost saving by reuse and recycling	Local availability for reducing foreign exchange	Improving indoor air quality	Improving thermal comfort	Reducing risk and provision of safety	Reducing noise	Social Acceptance	Aesthetic appearance	Local sourcing of raw materials for Improving employment opportunities	Conserving local architecture				
	MJ	kgCO2e						Rs	Rs	Rs	Rs	Rs	Rs	Rs													
BCB	1E+06	242429	3	3	4	2	4	912000	223840	76000	4	3	3	3	5	4	4496	3	4	5	4	4	4				
CSB	1E+06	257698	3	3	3	3	2	620000	256570	76000	3	3	3	2	3	3	5219	4	3	4	2	3	3				
CSEB	1E+06	230167	4	4	4	4	4	680000	223570	76000	4	4	2	3	4	4	4489	3	3	3	4	4	3				
Vector normalization	2E+06	422086	5.831	5.831	6.4031	5.385	6	1E+06	407328	1E+05	6.403	5.83	4.69	4.69	7.071	6.403	8222	5.831	5.831	7.07	6	6.4031	5.831				
Normalised matrix																											
BCB	0.601	0.574	0.514	0.514	0.625	0.371	0.667	0.704	0.550	0.577	0.625	0.514	0.640	0.640	0.707	0.625	0.547	0.514	0.686	0.707	0.667	0.625	0.686				
CSB	0.592	0.611	0.514	0.514	0.469	0.557	0.333	0.479	0.630	0.577	0.469	0.514	0.640	0.426	0.424	0.469	0.635	0.686	0.514	0.566	0.333	0.469	0.514				
CSEB	0.538	0.545	0.686	0.686	0.625	0.743	0.667	0.525	0.549	0.577	0.625	0.686	0.426	0.640	0.566	0.625	0.546	0.514	0.514	0.424	0.667	0.625	0.514				
Weights overall	10.7	7.9	9.1	5.7	5.7	3.9	2.7	7.3	7.6	3.0	2.7	1.7	1.9	3.3	2.9	4.0	3.8	4.1	1.9	1.7	1.6	1.7	5.0				
Multiplied with overall weights																								S+	S-	Pi	Rank
BCB	0.064	0.045	0.047	0.029	0.036	0.015	0.018	0.051	0.042	0.017	0.017	0.009	0.012	0.021	0.021	0.025	0.021	0.021	0.013	0.012	0.011	0.011	0.034	######	######	0.374	2
CSB	0.064	0.048	0.047	0.029	0.027	0.022	0.009	0.035	0.048	0.017	0.013	0.009	0.012	0.014	0.012	0.019	0.024	0.028	0.010	0.010	0.005	0.008	0.026	######	######	0.288	3
CSEB	0.058	0.043	0.062	0.039	0.036	0.029	0.018	0.038	0.042	0.017	0.017	0.012	0.008	0.021	0.017	0.025	0.021	0.021	0.010	0.007	0.011	0.011	0.026	######	######	0.853	1
Ideal best	0.058	0.043	0.062	0.039	0.036	0.029	0.018	0.035	0.042	0.017	0.017	0.012	0.012	0.021	0.021	0.025	0.021	0.028	0.013	0.012	0.011	0.011	0.034				
Ideal worst	0.064	0.048	0.047	0.029	0.027	0.015	0.009	0.051	0.048	0.017	0.013	0.009	0.008	0.014	0.012	0.019	0.024	0.021	0.010	0.007	0.005	0.008	0.026				

Figure 23: Case study applied in Excel form of Framework

	Saving energy	Reducing energy emissions	Reducing overexploitation of natural resources	Reducing waste	Reducing Hazardous or toxic content	Water efficiency	Reducing heat island effect	Reducing construction cost and increasing affordability	Reducing operational cost and cost saving due to energy reduction	Reducing maintenance cost	Reducing replacement cost and durability consideration	Reducing demolition cost	Salvage value	Cost saving by reuse and recycling	Local availability for reducing foreign exchange	Improving indoor air quality	Improving thermal comfort	Reducing risk and provision of safety	Reducing noise	Social Acceptance	Aesthetic appearance	Local sourcing of raw materials for Improving employment opportunities	Conserving local architecture				
	MJ	kgCO2e						Rs	Rs	Rs	Rs	Rs	Rs	Rs													
Alternative 1																											
Alternative 2																											
Alternative 3																											
Vector normalization	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0				
Normalised matrix																											
Alternative 1	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####				
Alternative 2	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####				
Alternative 3	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####				
Weights overall	10.7	7.9	9.1	5.7	5.7	3.9	2.7	7.3	7.6	3.0	2.7	1.7	1.9	3.3	2.9	4.0	3.8	4.1	1.9	1.7	1.6	1.7	5.0				
Multiplied with overall weights																								S+	S-	Pi	Rank
Alternative 1	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####	######	######	#####	#####
Alternative 2	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####	######	######	#####	#####
Alternative 3	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####	######	######	#####	#####
Ideal best	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####				
Ideal worst	#DIV/0!	######	######	######	######	#####	#####	######	######	#####	#####	####	####	#####	#####	#####	#####	#####	#####	####	####	######	#####				

Figure 24: Excel form of the developed framework

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APPENDIX - A

Questionnaire on eco-design building material selection in Sri Lanka: Level of Importance of eco-design parameters

A1: Request to participate in the survey 1: Cover letter

Dear Sir or Madam,

I am Sharon, a Master's student in the Department of Civil Engineering. My research supervisor is Prof. (Mrs.). C. Jayasinghe. I am developing a material selection framework for my MSc research.

I got your contact from the Green Building Council of Sri Lanka. I would like to conduct my survey among the Accredited Professionals of any Green Building Council.

As the first step of developing a framework with the aid of the Eco-design concept, I have identified four themes and sub-themes under each theme. I would be grateful if you can rate the importance of each sub-themes using the Likert scale provided in the survey. Also, I would be happy to include any other sub-themes in order to expand the scope.

I would like to conduct the above survey while having a meeting with you. I would be grateful to get a meeting with you in a time convenient to you. Herewith, I am attaching the survey sheet that is planned to be filled during the meeting.

Looking forward to hearing from you sir.

Thank you

Sharon Vanmathy Gurupatham
Research Assistant
Department of Civil Engineering
University Of Moratuwa

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Mobile:- (+94) 766312518
E mail:- sharonvanmathy@yahoo.com / sharonvanmathy@gmail.com

A2: Survey Document 1

Section 1 of 5

Questionnaire on eco-design building material selection in Sri Lanka: Level of Importance of eco-design parameters

We would be much grateful if you could kindly spend 10 minutes of your time to complete this survey, which will add significant value for improving building material selection in Sri Lanka.

Building material selection plays an important role in the construction industry in paving way for sustainable development. Several newer materials have emerged as alternatives to conventional building materials due to issues such as heavy energy consumption, high cost and scarcity, and over-exploitation of natural resources. With the higher number of alternatives, building material selection has become a difficult task that consumes significant time and cost. Hence, there should be a proper selection method that adheres to sustainable practices. Eco-design has been identified as a suitable tool for sustainable material selection.

Eco-design can be categorized into four themes:
1.) ecological,
2.) economic,
3.) social, and
4.) cultural.
Under each of the above themes, several sub-aspects are listed.

The main objective of the study is to develop a decision-support framework integrating all the aforementioned aspects and sub-aspects to select building envelope materials with the aid of the Eco-design concept. This decision support framework aims to achieve optimal building materials for residential buildings considering tropical climatic conditions.

This questionnaire survey focuses on collecting opinions on several objectives in order to achieve eco-design practices. You are expected to mark the level of importance of each objective on the Likert scale ranging from 1 to 5. The Likert scale has been explained below.
1- Not Important
2- Less Important
3- Neutral
4- Important
5- Very important

We can ensure that the results will be used for academic purposes only and Participation in this survey is voluntary. No identifying information about candidates collected by means of this survey will be shared. All the questions may appear the same. However, they differ significantly from each other.
If you want any clarifications, please feel free to consult Sharon Vanmathy. G using gurupathamsv.21@uom.lk

We recognize the significant time you consume on this survey, and we value your opinion. By completing this survey, you will help to uplift the Sri Lankan Construction Industry. Thank you for sharing your feedback and for your valuable time.

1. Email

2. Name

3. Current Profession

4. Years of experience in green projects:

<10		10-20		20-30		>30	

5. Number of green projects you were involved with

<5		5-10		10-15		15-20		>20	

6. Are you an Accredited Professional of any Green Building Council?

Yes		No	

7. Specify the council if yes. If no, please mention "Not applicable"

Section 2 of 5

Ecological parameters affecting sustainable material selection

Ecology is the study of interactions between living things, such as humans, and their natural surroundings.

Ecological parameters identified for sustainable material selection are Saving energy, reducing emissions, reducing overexploitation of natural resources, reducing waste, Reducing Hazardous or toxic content, Applicability with the fundamentals, Water efficiency and Reducing heat island effect.

8. You are expected to mark the level of importance of the ecological sub-themes provided "1-Not Important 2-Less Important 3-Neutral 4-Important 5-Very Important".

	1	2	3	4	5
Saving energy					
Reducing energy emissions					
Reducing overexploitation of natural resources					
Reducing waste					
Reducing Hazardous or toxic content					
Water efficiency					
Reducing the heat island effect					

9. In addition to the aforementioned sub-themes, please suggest if there are any other ecological sub-themes you think as contributing to sustainable material selection and provide the level of importance (1-5) of them.

Section 3 of 5

Economic parameters affecting sustainable material selection

The supply of money, as well as the production and consumption of products and services, make up the economy. In the building industry, cost effectiveness is crucial. Every design is evaluated in terms of price.

Economic parameters identified for sustainable material selection over the life cycle of a building are Reducing construction cost and increasing affordability, Reducing operational cost and cost saving due to energy reduction, Reducing maintenance cost, Reducing replacement cost and durability consideration, Reducing demolition cost, Salvage value, Cost saving by reuse and recycling, Local availability to reduce foreign exchange.

10. You are expected to mark the level of importance of the economic sub-themes provided "1-Not Important 2-Less Important 3-Neutral 4-Important 5-Very Important".

	1	2	3	4	5
Reducing construction costs and increasing affordability					
Reducing operational costs and cost savings due to energy reduction					
Reducing maintenance cost					
Reducing replacement cost and durability consideration					
Reducing demolition cost					
Salvage value					
Cost saving by reuse and recycling					
Local availability for reducing foreign exchange					

11. In addition to the aforementioned sub-themes, please suggest if there are any other economic sub-themes you think as contributing to sustainable material selection and provide the level of importance (1-5) of them.

____

Section 4 of 5

Social parameters affecting sustainable material selection

Social characteristics are what people have in common within a particular society.

Social parameters identified for sustainable material selection are Improving indoor air quality, improving thermal comfort, reducing risk and provision of safety (fire, Explosion, Radiation), Reducing noise (acoustic performance of material), Social acceptance, Aesthetic appearance, and Improving employment opportunities.

12. You are expected to mark the level of importance of the social sub-themes provided "1-Not Important 2-Less Important 3-Neutral 4-Important 5-Very Important".

	1	2	3	4	5
Improving indoor air quality					
Improving thermal comfort					
Reducing risk and provision of safety					
Reducing noise					
Social Acceptance					
Aesthetic appearance					
Local sourcing of raw materials for Improving employment opportunities					

13. In addition to the aforementioned sub-themes, please suggest if there are any other social sub-themes you think as contributing to sustainable material selection and provide the level of importance (1-5) of them.

___

Section 5 of 5

Cultural parameters affecting sustainable material selection

A given group or society's members' shared beliefs, practices, artifacts, and other traits make up its culture.

The cultural parameter identified for sustainable material selection is Conserving local architecture.

14. You are expected to mark the level of importance of the cultural sub-theme provided "1-Not Important 2-Less Important 3-Neutral 4-Important 5-Very Important".

	1	2	3	4	5
Conserving local architecture					

15. In addition to the aforementioned sub-themes, please suggest if there are any other Cultural sub-themes you think as contributing to sustainable material selection and provide the level of importance (1-5) of them.

___

Thank you for your valuable time

APPENDIX – B

AQuestionnaire on eco-design building material selection in Sri Lanka: Pair-wise comparison of eco-design parameters

B1: Request to participate in the survey 2: Cover letter

Dear Sir,

Hope you are doing great.

Thank you for you your contribution to the survey for finding the level of importance of eco-design parameters.

As the next step of my research, I am carrying out a pairwise comparison of themes and sub-themes that are finalized in the previous survey.

It would be highly appreciated if you could fill out a survey response. Please find the attached questionnaire.

Thank you for your time and consideration.

Sincerely yours,
Sharon Vanmathy Gurupatham
Research Assistant
Department of Civil Engineering
University Of Moratuwa

Contact:
Mobile:- (+94) 766312518
E mail:- sharonvanmathy@yahoo.com / sharonvanmathy@gmail.com

B2: Survey Document 2

Section 1 of 4

Questionnaire on eco-design building material selection in Sri Lanka: Pair-wise comparison of eco-design parameters

We would be much grateful if you could kindly spend 20 minutes of your time to complete this survey, which will add significant value for improving building material selection in Sri Lanka.
Building material selection plays an important role in the construction industry in paving way for sustainable development. Several newer materials have emerged as alternatives to conventional building materials due to issues such as heavy energy consumption, high cost and scarcity, and over-exploitation of natural resources. With the higher number of alternatives, building material selection has become a difficult task that consumes significant time and cost. Hence, there should be a proper selection method that adheres to sustainable practices. Eco-design has been identified as a suitable tool for sustainable material selection.

Eco-design can be categorized into four themes:
1.) ecological,
2.) economic,
3.) social, and
4.) cultural.
Under each of the above themes, several sub-themes are listed.

The main objective of the study is to develop a decision-support framework integrating all the aforementioned aspects and sub-aspects to select building envelope materials with the aid of the Eco-design concept. This decision support framework aims to achieve optimal building materials for residential buildings considering tropical climatic conditions.

This questionnaire survey focuses on collecting opinions on several objectives in order to achieve eco-design practices. You are expected to choose an option out of the pairs of options provided and then have to mark the level of importance of it over the other on liked scale from 1 to 9 where 1 indicates that they are of equal importance and 9 indicates that one is showing extreme importance than the other. The Likert scale is such that;

1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme Importance
2,4,6,8	Intermediate values between the two adjacent judgments

We can ensure that the results will be used for academic purposes only and Participation in this survey is voluntary. No identifying information about candidates collected by means of this survey will be shared. All the questions may appear the same. However, they differ significantly from each other.
If you want any clarifications, please feel free to consult Sharon Vanmathy. G using gurupathamsv.21@uom.lk

We recognize the significant time you consume on this survey, and we value your opinion. By completing this survey, you will help to uplift the Sri Lankan Construction Industry. Thank you for sharing your feedback and for your valuable time.

1. Email
___
2. Name
___

Main themes of eco-design

The themes identified under the concept of eco-design are Ecological, Economic, social, and cultural. Please compare each theme with one another and complete this section.

3. Which of the below themes is much more important than the other?

Ecological theme		Economic theme		Both are equally important	

4. How much do you think the option chosen by you in the previous question is more important than the other?

1		2		3		4		5		6		7		8		9	

5. Which of the below themes is much more important than the other?

Ecological theme		Social theme		Both are equally important	

6. How much do you think the option chosen by you in the previous question is more important than the other?

1		2		3		4		5		6		7		8		9	

7. Which of the below themes is much more important than the other?

Ecological theme		Cultural theme		Both are equally important	

8. How much do you think the option chosen by you in the previous question is more important than the other?

1		2		3		4		5		6		7		8		9	

9. Which of the below themes is much more important than the other?

Economic l theme		Social theme		Both are equally important	

10. How much do you think the option chosen by you in the previous question is more important than the other?

1		2		3		4		5		6		7		8		9	

11. Which of the below themes is much more important than the other?

Economic l theme		Cultural theme		Both are equally important	

12. How much do you think the option chosen by you in the previous question is more important than the other?

1		2		3		4		5		6		7		8		9	

13. Which of the below themes is much more important than the other?

Social l theme		Cultural theme		Both are equally important	

14. How much do you think the option chosen by you in the previous question is more important than the other?

1		2		3		4		5		6		7		8		9	

Section 2 of 4

Ecological sub-themes

Sub-themes such as Saving energy, Reducing emissions, Reducing overexploitation of natural resources, Reducing waste, Reducing Hazardous or toxic content, Water efficiency, and Reducing the heat island effect have been finalized for the material selection framework. Please compare each ecological sub-theme with one another and complete this section.

15. Which of the below ecological sub-themes is much more important than the other?

Saving Energy		Reducing energy emissions		Both are equally important	

16. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

17. Which of the below ecological sub-themes is much more important than the other?

Saving Energy		Reducing overexploitation of natural resources		Both are equally important	

18. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

19. Which of the below ecological sub-themes is much more important than the other?

Saving Energy		Reducing waste		Both are equally important	

20. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

21. Which of the below ecological sub-themes is much more important than the other?

Saving Energy		Reducing Hazardous or toxic content		Both are equally important	

22. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

23. Which of the below ecological sub-themes is much more important than the other?

Saving Energy		Water efficiency		Both are equally important	

24. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

25. Which of the below ecological sub-themes is much more important than the other?

Saving Energy		Reducing the heat island effect		Both are equally important	

26. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

27. Which of the below ecological sub-themes is much more important than the other?

Reducing energy emissions		Reducing overexploitation of natural resources		Both are equally important	

28. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

29. Which of the below ecological sub-themes is much more important than the other?

Reducing energy emissions		Reducing waste		Both are equally important	

30. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

31. Which of the below ecological sub-themes is much more important than the other?

Reducing energy emissions		Reducing Hazardous or toxic content		Both are equally important	

32. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

33. Which of the below ecological sub-themes is much more important than the other?

Reducing energy emissions		Water efficiency		Both are equally important	

34. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

35. Which of the below ecological sub-themes is much more important than the other?

Reducing energy emissions		Reducing the heat island effect		Both are equally important	

36. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

37. Which of the below ecological sub-themes is much more important than the other?

Reducing overexploitation of natural resources		Reducing waste		Both are equally important	

38. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

39. Which of the below ecological sub-themes is much more important than the other?

Reducing overexploitation of natural resources		Reducing Hazardous or toxic content		Both are equally important	

40. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

41. Which of the below ecological sub-themes is much more important than the other?

Reducing overexploitation of natural resources		Water efficiency		Both are equally important	

42. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

43. Which of the below ecological sub-themes is much more important than the other?

Reducing overexploitation of natural resources		Reducing the heat island effect		Both are equally important	

44. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

45. Which of the below ecological sub-themes is much more important than the other?

Reducing waste		Reducing Hazardous or toxic content		Both are equally important	

46. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

47. Which of the below ecological sub-themes is much more important than the other?

Reducing waste		Water efficiency		Both are equally important	

48. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

49. Which of the below ecological sub-themes is much more important than the other?

Reducing waste		Reducing the heat island effect		Both are equally important	

50. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

51. Which of the below ecological sub-themes is much more important than the other?

Reducing Hazardous or toxic content		Water efficiency		Both are equally important	

52. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

53. Which of the below ecological sub-themes is much more important than the other?

Reducing Hazardous or toxic content		Reducing the heat island effect		Both are equally important	

54. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

55. Which of the below ecological sub-themes is much more important than the other?

Water efficiency		Reducing the heat island effect		Both are equally important	

56. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

Section 3 of 4

Economic sub-themes

Sub-themes such as Reducing construction cost and increasing affordability, Reducing operational cost and cost saving due to energy reduction, Reducing maintenance cost, Reducing replacement cost and durability consideration, Reducing demolition cost, Salvage value, Cost saving by reuse and recycling, Local availability to reduce foreign exchange. Please compare each economic sub-theme with one another and complete this section.

57. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Reducing operational costs and cost savings due to energy reduction		Both are equally important	

58. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

59. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Reducing maintenance cost		Both are equally important	

60. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

61. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Reducing replacement cost and durability consideration		Both are equally important	

62. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

63. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Reducing demolition cost		Both are equally important	

64. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

65. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Salvage value		Both are equally important	

66. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

67. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Cost saving by reuse and recycling		Both are equally important	

68. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

69. Which of the below economic sub-themes is much more important than the other?

Reducing construction costs and increasing affordability		Local availability for reducing foreign exchange		Both are equally important	

70. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

71. Which of the below economic sub-themes is much more important than the other?

Reducing operational costs and cost savings due to energy reduction		Reducing maintenance cost		Both are equally important	

72. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

73. Which of the below economic sub-themes is much more important than the other?

Reducing operational costs and cost savings due to energy reduction		Reducing replacement cost and durability consideration		Both are equally important	

74. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

75. Which of the below economic sub-themes is much more important than the other?

Reducing operational costs and cost savings due to energy reduction		Reducing demolition cost		Both are equally important	

76. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

77. Which of the below economic sub-themes is much more important than the other?

Reducing operational costs and cost savings due to energy reduction		Salvage value		Both are equally important	

78. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

79. Which of the below economic sub-themes is much more important than the other?

Reducing operational costs and cost savings due to energy reduction		Cost saving by reuse and recycling		Both are equally important	

80. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

81. Which of the below economic sub-themes is much more important than the other?

Reducing operational costs and cost savings due to energy reduction		Local availability for reducing foreign exchange		Both are equally important	

82. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

83. Which of the below economic sub-themes is much more important than the other?

Reducing maintenance cost		Reducing replacement cost and durability consideration		Both are equally important	

84. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

85. Which of the below economic sub-themes is much more important than the other?

Reducing maintenance cost		Reducing demolition cost		Both are equally important	

86. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

87. Which of the below economic sub-themes is much more important than the other?

Reducing maintenance cost		Salvage value		Both are equally important	

88. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

89. Which of the below economic sub-themes is much more important than the other?

Reducing maintenance cost		Cost saving by reuse and recycling		Both are equally important	

90. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

91. Which of the below economic sub-themes is much more important than the other?

Reducing maintenance cost		Local availability for reducing foreign exchange		Both are equally important	

92. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

93. Which of the below economic sub-themes is much more important than the other?

Reducing replacement cost and durability consideration		Reducing demolition cost		Both are equally important	

94. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

95. Which of the below economic sub-themes is much more important than the other?

Reducing replacement cost and durability consideration		Salvage value		Both are equally important	

96. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

97. Which of the below economic sub-themes is much more important than the other?

Reducing replacement cost and durability consideration		Cost saving by reuse and recycling		Both are equally important	

98. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

99. Which of the below economic sub-themes is much more important than the other?

Reducing replacement cost and durability consideration		Local availability for reducing foreign exchange		Both are equally important	

100. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

101. Which of the below economic sub-themes is much more important than the other?

Reducing demolition cost		Salvage value		Both are equally important	

102. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

103. Which of the below economic sub-themes is much more important than the other?

Reducing demolition cost		Cost saving by reuse and recycling		Both are equally important	

104. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

105. Which of the below economic sub-themes is much more important than the other?

Reducing demolition cost		Local availability for reducing foreign exchange		Both are equally important	

106. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

107. Which of the below economic sub-themes is much more important than the other?

Salvage value		Cost saving by reuse and recycling		Both are equally important	

108. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

109. Which of the below economic sub-themes is much more important than the other?

Salvage value		Local availability for reducing foreign exchange		Both are equally important	

110. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

111. Which of the below economic sub-themes is much more important than the other?

Cost saving by reuse and recycling		Local availability for reducing foreign exchange		Both are equally important	

112. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

Section 4 of 4

Social sub-themes

Sub-themes such as Improving indoor air quality, Improving thermal comfort, Reducing risk and provision of safety(fire, Explosion, Radiation), Reducing noise (acoustic performance of material), Social acceptance, Aesthetic appearance, and Improving employment opportunities. Please compare each social sub-theme with one another and complete this section.

113. Which of the below social sub-themes is much more important than the other?

Improving indoor air quality		Improving thermal comfort		Both are equally important	

114. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

115. Which of the below social sub-themes is much more important than the other?

Improving indoor air quality		Reducing risk and provision of safety		Both are equally important	

116. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

117. Which of the below social sub-themes is much more important than the other?

Improving indoor air quality		Reducing noise		Both are equally important	

118. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

119. Which of the below social sub-themes is much more important than the other?

Improving indoor air quality		Social Acceptance		Both are equally important	

120. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

121. Which of the below social sub-themes is much more important than the other?

Improving indoor air quality		Aesthetic appearance		Both are equally important	

122. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

123. Which of the below social sub-themes is much more important than the other?

Improving indoor air quality		Local sourcing of raw materials for Improving employment opportunities		Both are equally important	

124. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

125. Which of the below social sub-themes is much more important than the other?

Improving thermal comfort		Reducing risk and provision of safety		Both are equally important	

126. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

127. Which of the below social sub-themes is much more important than the other?

Improving thermal comfort		Reducing noise		Both are equally important	

128. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

129. Which of the below social sub-themes is much more important than the other?

Improving thermal comfort		Social Acceptance		Both are equally important	

130. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

131. Which of the below social sub-themes is much more important than the other?

Improving thermal comfort		Aesthetic appearance		Both are equally important	

132. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

133. Which of the below social sub-themes is much more important than the other?

Improving thermal comfort		Local sourcing of raw materials for Improving employment opportunities		Both are equally important	

134. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

135. Which of the below social sub-themes is much more important than the other?

Reducing risk and provision of safety		Reducing noise		Both are equally important	

136. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

137. Which of the below social sub-themes is much more important than the other?

Reducing risk and provision of safety		Social Acceptance		Both are equally important	

138. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

139. Which of the below social sub-themes is much more important than the other?

Reducing risk and provision of safety		Aesthetic appearance		Both are equally important	

140. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

141. Which of the below social sub-themes is much more important than the other?

Reducing risk and provision of safety		Local sourcing of raw materials for Improving employment opportunities		Both are equally important	

142. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

143. Which of the below social sub-themes is much more important than the other?

Reducing noise		Social Acceptance		Both are equally important	

144. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

145. Which of the below social sub-themes is much more important than the other?

Reducing noise		Aesthetic appearance		Both are equally important	

146. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

147. Which of the below social sub-themes is much more important than the other?

Reducing noise		Local sourcing of raw materials for Improving employment opportunities		Both are equally important	

148. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

149. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

150. Which of the below social sub-themes is much more important than the other?

Social Acceptance		Aesthetic appearance		Both are equally important	

151. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

152. Which of the below social sub-themes is much more important than the other?

Social Acceptance		Local sourcing of raw materials for Improving employment opportunities		Both are equally important	

153. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

154. Which of the below social sub-themes is much more important than the other?

Aesthetic appearance		Local sourcing of raw materials for Improving employment opportunities		Both are equally important	

155. How much do you think the option chosen by you in the previous question is more important than the other option?

1		2		3		4		5		6		7		8		9	

Thank you for your valuable time

B3: Summary tables for Survey 2

Summarized form of the Questionnaire on eco-design building material selection in Sri Lanka: Pair-wise comparison of eco-design parameters

Please fill in the importance of a theme or subtheme provided over the other. The results could be used for AHP calculations to propose weights.
Use the below Likert scale to mark the importance of one aspect over the other.

Score	Level of importance over the other factor
1	Equal importance
3	Moderate importance of one over another
5	Essential or strong importance
7	Very strong importance
9	Extreme Importance
2,4,6,8	Intermediate values between the two adjacent judgments

Procedure:
An Example has been provided for you. In this example, factor A is 5 times more important than B while it is 3 times more important than C. Factor C is 2 times more important than B.

	A	B	C
A	1	5	3
B		1	1/2
C			1

Please follow the above example and fill in the tables below

Task 1
The table below shows the identified themes of eco-design. Please mark the level of importance of the themes over the others.

	Ecological	Economic	Social	Cultural
Ecological	1			
Economic		1		
Social			1	
Cultural				1

Task 2:
The table below shows the identified sub-themes under the ecological theme. Please mark the level of importance of the themes over the others

	Saving energy	Reducing energy emissions	Reducing overexploitation of natural resources	Reducing waste	Reducing Hazardous or toxic content	Water efficiency	Reducing the heat island effect
Saving energy	1						
Reducing energy emissions		1					
Reducing overexploitation of natural resources			1				
Reducing waste				1			
Reducing Hazardous or toxic content					1		
Water efficiency						1	
Reducing the heat island effect							1

Task 3:
The table below shows the identified sub-themes under the economic theme. Please mark the level of importance of the themes over the others.

	Reducing construction	Reducing operational costs and cost savings due to energy reduction	Reducing maintenance cost	Reducing replacement cost and durability	Reducing demolition cost	Salvage value	Cost saving by reuse and recycling	Local availability for reducing foreign
Reducing construction costs and increasing affordability	1							
Reducing operational costs and cost savings due to energy reduction		1						
Reducing maintenance cost			1					
Reducing replacement cost and durability				1				
Reducing demolition cost					1			
Salvage value						1		
Cost saving by reuse and recycling							1	
Local availability for reducing foreign exchange								1

Task 4:

The table below shows the identified sub-themes under the social theme. Please mark the level of importance of the themes over the others.

	Improving indoor air quality	Improving thermal comfort	Reducing risk and provision of safety (fire, Explosion, Radiation)	Reducing noise (acoustic performance of material)	Social Acceptance	Aesthetic appearance	Local sourcing of raw materials for Improving
Improving indoor air quality	1						
Improving thermal comfort		1					
Reducing risk and provision of safety (Fire, Explosion, Radiation)			1				
Reducing noise (acoustic performance of material)				1			
Social Acceptance					1		
Aesthetic appearance						1	
Local sourcing of raw materials for Improving employment opportunities							1

APPENDIX - C

Application to the framework

C1: Request to participate in the survey 3: Cover letter

Dear Sir,

I am Sharon, a Masters' student from the University of Moratuwa. I have developed a material selection framework for my research. Accordingly, I am trying to validate it with 3 alternative walling materials. I am comparing Cement Stabilized Earth Blocks (CSEB) with conventional materials such as Burnt Clay Bricks (BCB) and Cement Sand Blocks (CSB).

This is an eco-design-based material selection where several sub-themes are identified. The performance related to certain sub-themes is quantified using calculations as well as energy modeling using Design Builder. In order to quantify the rest of the parameters I am using a survey-based approach.

I would like to collect your opinion regarding the same. Herewith I am attaching the document in which you can fill your opinions. Or else, If you prefer a meeting regarding the same could you please give me a time.

Your response is highly appreciated. Waiting to hearing from you.

Thank you

Sincerely yours,

Sharon Vanmathy Gurupatham
Research Assistant
Department of Civil Engineering
University Of Moratuwa

Contact:
Mobile:- (+94) 766312518
E mail:- sharonvanmathy@yahoo.com / sharonvanmathy@gmail.com

C2: Survey Document: 3

Questionnaire on comparison of walling materials with the aid of Eco-design practices

This questionnaire survey focuses on the comparison of walling materials with the aid of Eco-design which includes goals such as economic, environmental, social, and cultural aspects.
The quantifiable sub-themes under each goal are computed and the rest of the sub-themes identified are presented below in this survey.
You are expected to give scores from 1 to 5 for each objective for the different materials considered in the study. Please find the Likert scale to be used for this survey
1- Low
2- Below average
3- Average
4- Good
5- Excellent
The materials considered are Cement Stabilized Earth Blocks (CSEB), Burnt Clay Bricks (BCB), and Cement Sand Blocks (CSB).

Thank you for your Valuable time

1. Email

   ___

2. Name

   ___

3. Current Profession

   ___

4. Experience with CSEB material

Research		Industry		Other	

5. Years of experience with CSEB material

   ___

Opinion on the performance of materials based on sub-themes

Please give scores from 1 to 5 for the below sub-themes for materials such as Cement Stabilises Earth Blocks(CSEB), Burnt Clay Bricks(BCB), and Cement Sand Blocks(CSB).

6. Give your opinion on the performance of the below materials based on "Reducing overexploitation of natural resources".

	1	2	3	4	5
BCB					

CSB					
CSEB					

7. Give your opinion on the performance of the below materials based on " Reducing waste".

	1	2	3	4	5
BCB					
CSB					
CSEB					

8. Give your opinion on the performance of the below materials based on " Reducing hazardous or toxic content".

	1	2	3	4	5
BCB					
CSB					
CSEB					

9. Give your opinion on the performance of the below materials based on " Water efficiency".

	1	2	3	4	5
BCB					
CSB					
CSEB					

10. Give your opinion on the performance of the below materials based on " Reducing heat island effect".

	1	2	3	4	5
BCB					
CSB					
CSEB					

11. Give your opinion on the performance of the below materials based on " Reducing replacement cost and durability considerations".

	1	2	3	4	5
BCB					
CSB					
CSEB					

12. Give your opinion on the performance of the below materials based on " Reducing demolition cost".

	1	2	3	4	5

BCB					
CSB					
CSEB					

13. Give your opinion on the performance of the below materials based on " Salvage value ".

	1	2	3	4	5
BCB					
CSB					
CSEB					

14. Give your opinion on the performance of the below materials based on " Cost saving by reuse and recycling".

	1	2	3	4	5
BCB					
CSB					
CSEB					

15. Give your opinion on the performance of the below materials based on " Local availability for reducing foreign exchange".

	1	2	3	4	5
BCB					
CSB					
CSEB					

16. Give your opinion on the performance of the below materials based on " Improving indoor air quality".

	1	2	3	4	5
BCB					
CSB					
CSEB					

17. Give your opinion on the performance of the below materials based on " Reducing risk (fire, explosion, radiation) and provision of safety".

	1	2	3	4	5
BCB					
CSB					
CSEB					

18. Give your opinion on the performance of the below materials based on " "Reducing noise" (Acoustic performance of material).

	1	2	3	4	5
BCB					
CSB					
CSEB					

19. Give your opinion on the performance of the below materials based on " Social Acceptance".

	1	2	3	4	5
BCB					
CSB					
CSEB					

20. Give your opinion on the performance of the below materials based on " Aesthetic Appearance".

	1	2	3	4	5
BCB					
CSB					
CSEB					

21. Give your opinion on the performance of the below materials based on " Local sourcing of materials to improve employment opportunities".

	1	2	3	4	5
BCB					
CSB					
CSEB					

22. Give your opinion on the performance of the below materials based on " Conserving local architecture".

	1	2	3	4	5
BCB					
CSB					
CSEB					

C3: Summary tables for Survey 3

Request to suggest your opinions on the performance of materials

I have developed a material selection framework for my research based on Eco-design which is a tool for sustainability. I have identified various aspects of the eco-design concept. Also, I have concluded weights of each aspect contribute to eco-design-based material selection. However, in order to validate the framework, I decided to compare alternative materials. Accordingly, I am comparing 3 materials namely, Burnt Clay Bricks (BCB), Cement Sand Blocks (CSB), and Cement stabilized earth Blocks (CSEB).

Please utilize the five-point scale; 1-Low, 2-Below average, 3-Average, 4-Good, 5-Excellent; to fill the table provided to mark your opinions on the performance of the given materials concerning the aspects provided.

Aspect	BCB	CSB	CSEB
Reducing overexploitation of natural resources			
Reducing waste			
Reducing Hazardous or toxic content			
Water efficiency			
Reducing the heat island effect			
Reducing replacement cost and durability			
Reducing demolition cost			
Salvage value			
Cost saving by reuse and recycling			
Local availability for reducing foreign exchange			
Improving indoor air quality			
Reducing risk and provision of safety			
Reducing noise			
Social Acceptance			
Aesthetic appearance			
Local sourcing of raw materials for Improving employment opportunities			
Conserving local architecture			