DEVELOPMENT OF A FRAMEWORK FOR SUSTAINABLE BUILDING ASSESSMENT

Submitted in partial fulfillment of the requirements for the award of the degree of

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in

CIVIL ENGINEERING

by

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CERTIFICATE

This is to certify that the thesis entitled "**DEVELOPMENT OF A FRAMEWORK FOR SUSTAINABLE BUILDING ASSESSMENT**" being submitted by **Mr. ARUKALA SUCHITH REDDY** (**Roll No. 716105**) for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Department of Civil Engineering of National Institute of Technology Warangal is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for the award of any degree.

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DECLARATION

This is to certify that the work presented in the thesis entitled "**DEVELOPMENT OF A FRAMEWORK FOR SUSTAINABLE BUILDING ASSESSMENT**" is a bonafide work done by me under the supervision of **Prof. P. RATHISH KUMAR & Prof. P. ANAND RAJ** and was not submitted elsewhere for the award of any degree. I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea / data / fact / source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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ABSTRACT

The human race is now facing a looming crisis of resource depletion and global warming. Population trends in recent years indicate rapid urbanization with more than half of the world's population living in urban settings. This problem poses several challenges to the governing bodies including the pressing demand for providing amicable living conditions vis-à-vis housing, transportation, health, education and infrastructure facilities. A mismanaged, haphazard approach to population growing needs, lead to degradation of the environment and undoes the progress in sustainable development achieved so far. To facilitate living conditions with a minimal backlash on the limited resources, it is imperative to make a transition towards sustainable urban development.

The built environment was recognized as the largest contributor to changes in the environment. The construction, operation, and maintenance of buildings are estimated to account for approximately 40%–50% of all energy usage and emissions of GHG globally. There may be economic benefits from the investments in infrastructural projects, but they do cause more negative impacts on social and environmental issues. From the construction industry perspective, it is believed that sustainability should take into account the protection of a regional uniqueness incorporating localized architecture depending upon the local needs of the people despite their economic status. It is understood that the sustainability in construction industry refers to habitat comfort, the durability and service life of the structure, optimum utilization of resources, efficient utilization of energy, water, land, protection of the environment, and developing social integrity. Sustainable construction simply mean efficient use of natural resources, minimize negative impact on the ecology and improve the human satisfaction and quality of life. Sustainable urban development has to achieve three goals of sustainability viz., economic, social, and environmental in order to be well implemented.

Developing countries often face challenges and priorities that are different from those of advanced countries. These include, but are not limited to infrastructure and housing deficit, rapidly rising population, skill shortage, social inequity and relatively unstable political climate. To accomplish the need for sustainability, it is vital to understand the interrelationship between social needs, economic feasibility, and environmental impacts. The basic needs include food, clothing and shelter and above all, the ability to

live at higher standards i.e., economical aspects. Therefore, promoting and incorporating sustainability is nothing but balancing the main three pillars, ecologically termed as sustainable development and this approach is known to be ‘Triple-Bottom-Line’ (TBL) approach.

To balance economic growth with sustainable development in the building sector, many countries around the world have come up with several building assessment tools to assess the building’s sustainability performance. A Sustainable building is designed to minimize the environmental impacts and optimize resource consumption during various stages of its life cycle, for instance, Leadership in Energy and Environment (LEED) in the US, Building Research Establishment Environmental Assessment Method (BREEAM) of the UK, Comprehensive Assessment System for Built Environment Efficiency (CASBEE) of Japan, Green Rating for Integrated Habitat Assessment (GRIHA) of India, etc. Studies conducted in this field have indicated that these building assessment tools are based mainly on the environmental component of sustainability and that there is a necessity to include economic, social, institutional, technical and cultural factors in the assessment tools (Abdul-Rahman et al. 2016; Banani et al. 2016; Chang et al. 2013; Chen et al. 2017; Erdogan and Šaparauskas, 2019; Henriksson, 2010; Hussin et al. 2013; Magent et al. 2009; Todd et al. 2010; UNEP SBCI, 2010; Zarghami et al. 2018)

Most of the building assessment studies are oriented towards environmental indicator only (Abdul-Rahman et al. 2016; Chan and Chan, 2004; Ding, 2008; Giddings et al. 2002; Jamilus et al. 2013; Riffat et al. 2016; Vatalis et al. 2013; Waris et al. 2014). This indicates disregard to social and economic aspects of sustainability, which could further lead to ecological imbalance and thereby, miss the real goal of sustainable development, though, some of them focused on measuring sustainable performance considering one or more indicators (Kylili et al. 2016). It is significant to consider environmental, social, and economic dimensions (TBL approach) while assessing the building performance towards sustainability. However, the TBL approach has been claimed to distract and limit research, as not all local-level development issues are clearly either environmental, social, or economic (Alwaer et al. 2010a, 2010b; Anadon et al. 2016; Cancino et al. 2015; Chan and Chan, 2004; Kaya and Kahraman, 2014; Kulkarni et al. 2017; Liu and Lin, 2016; Mahmoudkelaye et al. 2017; Teplý et al. 2018).

The criteria like energy efficiency, indoor air quality, water efficiency, water management, pollution, sustainable sites, human comfort, innovation, material efficiency, and renewable energy etc in most of the studies have assumed to orient towards only one or more indicators like environmental, cultural, institutional, socio-economic and political etc., and ignore the significance over other indicators. For example, the 'pollution' criteria considered under 'Environmental' indicator is presumed to be insignificant towards another indicator like social and economic indicators and evaluated the criteria measure towards sustainability. The interrelationship between indicators, criteria, and interdependency among criteria and indicators has been neglected. Few of them considered TBL approach but failed to incorporate the technological advances (Akizu-gardoki et al. 2018; Al-Jebouri e tal. 2017; Ghodoosi et al. 2018; Laedre et al. 2015; Patil et al. 2016) which have always been the cornerstone in mitigating the unavoidable side-effects of development and in surpassing the limits/constraints dictated by the other indicators of sustainability (Park et al. 2017). It was observed that it is imperative to incorporate the Technological indicator by rejuvenating ideas of reduce, reuse, recycle, renovate, and repair into implementable solutions. The holistic view under the main umbrella i.e. TBL along with Technological indicator will balance the construction eco-system for achieving sustainability. Thus, there arises a need to integrate Social, Environmental, Economic and Technological (SEET) indicators for assessing the sustainability of building construction. There exists a cultural, ethical and economic dissimilarity between the developed and developing countries to understand and implement the sustainability in the construction industry.

The present study is focused on implementation and adoption of sustainable principles in building industry, to monitor the performance and identify the specific indicators and criteria. It is noteworthy to observe here that, mere transfer of indicators and criteria from an existing building assessment framework developed for a particular country is not suitable to other country due to differences in regional, culture, heritage and geographical conditions of another country. The transfer of Technology can be successful only when current priorities and prevailing conditions of specific location are incorporated. Hence, the assessment tool developed for one nation or area may not be acceptable for another area. The present study aims at promoting, monitoring and evaluating sustainable building with regard to SEET indicators in order to achieve sustainable built environment for better quality of life.

Assessment of building performance requires suitable criteria and indicators and active participation of experts from various domains of construction industry to consider real-time conditions of a specific region. This involves multiple perceptions from decision-makers considering multiple dimensions and criteria for achieving a single goal. For a framework to be well-developed, a reliable weighting structure has to be proposed to accept and institutionalize the importance of a wide variety of sustainable construction concerns. Most of these methods as said earlier are obstructed by components such as climatic circumstances, regional and geographic differences, culture, socio-economic elements. For this reason every nation/area needs their own strategical plan to assess whether the construction industry is implementing appropriate sustainability practices. The Analytical Hierarchy Process (AHP) method is a well-known Multi-Criteria Decision Making (MCDM) technique for determining the weights for any kind of hierarchical structure in various domains. However, it is not effective to handle the uncertainty and imprecision of the decision-maker. Fuzzy set theory on the other hand captures the vagueness, uncertainty, and impreciseness of the decision-maker.

From a detailed review of the literature, the following are the observations

A detailed literature review was carried on sustainable development with a focus on building assessment tool suitable to regional variations, climate conditions, culture, heritage and topographical conditions of developing countries like India, based on SEET aspects. The literature study was also aimed at emphasizing the adoption of existing tools for their suitability, similarities and differences and further checked for the possibility of adapting to the prevailing conditions without the need for life cycle inventory data. The following are the observations reported from the literature review:

1) There are studies reported on the factors influencing sustainable construction and that affect the building performance towards sustainability.
2) Most of the work reported the building performance considering the environmental dimension only. Some of them considered both environmental and economic dimensions to observe the impacts, burdens and cost implications.

3) There are very few studies reported on the building assessment based on TBL approach i.e., Social, Environmental and Economic dimension. However, these lack the interrelationship among the dimensions and it was noticed that the assessment tools developed for one nation or region might not be applicable to others.
4) It has been observed from the literature that, 'Technological' advances has always been the cornerstone in mitigating the unavoidable side-effects of development and in surpassing the limits/constraints dictated by the other indicators of sustainability vis-à-vis Social, Economic and Environmental.
5) It was felt that it is imperative to incorporate the technological dimension by rejuvenating ideas like reuse, recycle, reduce, renew and regenerate into implementable solutions of the existing TBL to achieve complete sustainable construction SEET indicators.
6) Most of the assessment tools utilized the Analytical Hierarchy Process (AHP), a Multi-Criterion Decision Making (MCDM) method to assess the relative weight.
7) The concept of fuzzy logic was utilized to capture the ambiguity and vagueness of the decision-makers. It can also be inferred that the Delphi Technique (DT) is preferable to reach a consensus for the identified criteria based on previous studies.
8) It is important to decide the applicable criteria and sub-criteria to be compatible with the Indian context, which exhibits a wide range of climates, cultures, and topographic features. This would enable implementing a domestic assessment method for measuring building performance.
9) It was observed that due to the unavailability of appropriate life cycle inventory data for building materials in developing countries like India, the existing assessment tools (GRIHA, LEED, and IGBC) have disregarded the material component while evaluating the sustainable building performance. Hence, there is a need to study the behavior of material performance towards sustainability.
10) It was also felt that there is a necessity to develop a handy Graphical User Interface (GUI) system, a self-assessment tool to estimate the sustainable building performance.

The scope of the present study includes the following

- Based on the available existing assessment tools, guidelines and policies, the criteria and attributes are identified considering regional context, climate conditions, culture, heritage, and topographical conditions.
- Assigning and standardizing the relative weights for sustainable indicators, criteria and establish inter-relationship between them.
- Distribute credit points to sustainable attributes corresponding to each criterion so as to quantify the building performance and thus generate a sustainable building performance score.
- Assess the material performance towards sustainability by generating a material index considering material life-cycle phases.
- Develop a Graphical User Interface (GUI) web portal using HTML, JavaScript and other tools and technologies to assess the building performance score and thus rate the building.

Based on the observations from the literature review, the following objectives are defined for the present investigation.

1) To identify and evaluate relative weights of sustainable criteria and indicators (SEET) and establish Inter-relationship between them based on existing tools (LEED, BREEAM, GRIHA, and IGBC), guidelines and policies.
2) To obtain the relevant quantifiable attributes and pre-requisites for each criterion and assign weights to them for assessing the building performance.
3) To quantify the building material index by integrating sustainable SEET indicators, factors influencing material sustainable performance and material life-cycle phases, without the need for inventory data.
4) To develop a sustainable building performance scoring system based on relative weights of criteria and global weights of sustainable attributes, and thus develop an automated GUI embedded Sustainable Building Assessment Tool (SBAT).

To achieve the above-mentioned objectives, a detailed program is designed and carried out in four different phases.

Phase - I

This phase is dealt in four stages: Comparing, identifying, evaluating relative weights and establishing interrelationship between indicators and criteria.

The significant criteria that can assess the sustainable performance of a building were identified based on the existing assessment tools (BREEAM, LEED, IGBC, and GRIHA), guidelines, policies and related publications considering local context, climatic conditions, culture, topography, and ethical aspects that prevail in developing countries like India. These criteria and sub-criteria are assessed and checked for the possibility of transfer and for adopting in the Indian context. Further, the identified criteria are refined and screened out using Delphi Technique (DT) and Relative Importance Index (RII) to reach a consensus on the diagnosed criteria their related attributes for quantification. Based on Six expert decision-makers belonging to categories such as Academicians, Engineers, Designers, Architects, Consultants, and Other Technocrats, the criteria whose value is more than or equal to 0.7 has been screened out for selecting the most significant attributes. A total of eight criteria and 37 attributes were established to evaluate and assess the building performance towards sustainability. For evaluating the relative weights of criteria and indicators, questionnaires were framed in such a way that the relative importance of criteria with respect to each indicator (SEET) is obtained on a seven point Likert scale. The consistency of the data is checked using Cronbach's Alpha coefficient before performing statistical methods. In order to capture the ambiguity and vagueness of the respondents to the questionnaires, fuzzy logic is integrated with AHP and termed as FAHP, a Hybrid Multi-Criteria Decision Method (HMCDM) for assigning the relative weights to indicators and criteria. To perform FAHP, a number of pairwise comparisons for the four sustainable indicators and eight sustainable criteria for each respondent (Total 58) were performed. A total of 346 [4 x 4] matrices were developed to assign relative weights to sustainable indicators (SEET). Similarly, a total of 232 [8 x 8] matrices were developed to assign the relative weight to sustainable criteria. The interrelated weights are then obtained by multiplying the relative weights of sustainable indicators and criteria. From the interrelated weights of criteria and indicators, the average weight is obtained by pooling along with the criteria with regard to SEET indicators to identify significant criteria.

Phase - II

This phase of work intends to quantitatively assess the eight criteria which were identified in the previous phase with suitable attributes considering various pre-requisites. The approach involves determining the relative weights to sustainable attributes, assigning global weights to pre-requisites for developing a Sustainable Building scoring system using FAHP to develop a SBAT. Further, to assess the attribute performance, the relative weights of criteria and their corresponding attributes are multiplied to get the global weight. Based on the global weights of attributes, the pre-requisites were allotted with credit points in order to quantify the building performance on the practical field.

Phase - III

Based on the comprehensive literature review, guidelines and policies, and existing assessment tools, 10 key sustainable factors were identified which were most relevant to the material assessment. Three different approaches have been established based on MCDM methods to assess the material prioritization based on the identified sustainable factors. Each method has its own significance and justification in selecting a sustainable material alternative. The three methods include (i) Entropy-based Fuzzy Technique for Order Preference by Similarity to Ideal Solution (EFTOPSIS). (ii) Material Sustainable Performance Score (MSPS) and (iii) Sustainable Material Performance Index (SMPI). All the methods utilized the same input data set received from 54 respondents based on 10 sustainable factors and indicators for evaluation. In this phase, five different alternatives of binder material aiming at developing a sustainable concrete has been investigated based on different methods. The prominently used binder material alternatives considered were – Ordinary Portland Cement (OPC), Pozzolanic Portland Cement Flyash based (PPC-F), Pozzolanic Portland Cement Slag based (PPC-S), Geopolymer (GP) and Composite Cement (CC).

Phase -IV

This phase of work emphasizes on developing preference-based sustainable building score and an overall SBPS considering SEET indicators. To differentiate the building performance towards sustainability, based on Sustainable building Performance Score (SBPS), the study proposes five different performance levels to categorize the building performance. Graphic User Interface (GUI) is developed for lucidity in use of SBAT, utilizing open-source software and technologies (Tomcat Apache server, JavaScript, Java Server Pages, and HTML). The GUI includes the background page, a methodology page and, an Input & Out page. The input page consists of Yes/No and percentage type of questionnaire, while, the output page consists of pictorial representations of sustainable building performance. The GUI will act as a self-assessment tool. Further, a QR code is embedded in the HTML web portal for the assessment tool to improve awareness and public outreach. To spread the utility and enrich the convenience of using SBAT, the QR code is embedded in the link given below.

The study identified the need for promoting and practicing sustainable design and adoption of sustainable principles enabling the transformation from the conventional to sustainable construction in India. The following conclusions are drawn from the present research work

1. A new Technological dimension has been incorporated in the existing Triple Bottom Line (TBL) approach by introducing the concept of 5R’s (Reduce, Recycle, Reuse, Renovate and Repair).
2. Eight criteria and 37 attributes have been tailored under Social, Environmental, Economic and Technological (SEET) indicators, to adapt to the Indian context considering climatic variations, local context, topography, culture, and heritage.
3. The Technological indicator with a normalized interrelated weight of 28.4% was highest among SEET indicators. Also, under the Technological indicator, the criterion ‘Material and Waste Management’ has attained the highest interrelated weight of 15.56%.
4. The relative weights of the criteria are obtained from the Eight focused expertise groups comprising of Academicians, Consultants, Contractors, Designers, Engineers, Architects, Suppliers and other stakeholders of the construction industry based on a structured questionnaire on a five-point Likert scale.
5. The eight proposed criteria include Water Efficiency (12.63%), Materials and Waste Management (13.96%), Health and Well-being (13.04%), Energy Efficiency (13.15%), Sustainable Sites (12.88%), Social Welfare (11.48%), Transportation (11.36%), and Management (11.49%). These criteria facilitate policymaking, formulate guidelines and develop the green building rating tool.

6. From the findings, it was observed that the relative weights of indicators are in the order of Environmental (30%), Technological (27%), Economic (22%), and Social (21%). Material and Waste management (MW) and Energy Efficiency (EE) attained the highest relative weights of 14.98% and 13.96% respectively.
7. The criteria, ‘Regionally available materials’ and ‘Renewable energy production’ attained global weights of 3.01% & 2.40% respectively among the various attributes chosen under technological indicator.
8. Ten significant factors viz., Climate change, Pollution, Construction & Demolition Waste, resource consumption, life cycle cost, Health & Safety, Local Economic Development, Recyclability and Reusability, Human Satisfaction, and Practicability & Flexibility were identified to assess the material performance based on content analysis.
9. Three methods (EFTOPSIS, MSPS, and SMPI) were used for assessing the material performance. These methods revealed the significance of adopting material life cycle phases in the selection of sustainable material, without the need for inventory data.
10. It was noted that the method ‘Sustainable Material Performance Index’ (SMPI) was found to be robust and flexible and was able to accommodate both qualitative and quantitative insights. Higher the SMPI value better is the material performance towards sustainability.
11. Among the five different binder material alternatives (OPC, PPC, PSC, GP, and CC) investigated, it was observed that Geopolymer (GP) is highly prioritized with an SMPI value of 10.63. This was evaluated based on MCDM methods.
12. The study witnessed the order of significance of the material life cycle as Post-construction (39%), Construction (32%) and Pre-construction (29%), based on analysis of Relative Ranking Index (RRI).
13. Among the 10 identified sustainable factors for material evaluation, the factors ‘Climate change’ and ‘Pollution’ has highest SMPI values in the three life-cycle phases.
14. The SMPI framework developed from the study facilitates valuable inputs to building professionals in selecting a sustainable material alternative, without the need for Life Cycle Inventory data.

15. The novel method of assessment of building (SBAT) using attribute global weights takes into account the sensitivity to suit the practices, issues, and priorities of local to a certain region.
16. A scoring system to evaluate the Sustainable Building Performance Score (SPBS) based on the allotted credits points to attributes was developed. Further, a five-star rating based on a number of credit points to categorize sustainable performance of the building, more robust than the other building assessment tools are evolved.
17. A Graphical User Interface (GUI) embedded with QR code is developed for the end-user and acts as a self-assessment tool to identify the potential gaps and improvements for attaining the status of a sustainable building.

Through the development of the SBAT framework, a new contribution has been made to the literature for assessing the buildings. The most important of those are as follows:

- The well-known existing assessment tools for building assessment tend to avoid explicit disclosure of the process based on which their methods are developed. This study not only proposes a theoretical model, but also, makes the methodology transparent.
- The basis of any building assessment method is embedded in its assessment indicators, criteria, attributes and prerequisites. The present study has disclosed the applicable criteria and attributes that form the main structure specific to Indian sustainable building assessment.
- Weighting systems are integral to reliable evaluation. This study has determined a weighting system for the approved criteria and attributes, which form the most applicable framework for the sustainability development of the built environment in India. The weighting system developed, includes a procedure (weights, interrelations, rating formulas, benchmarking expression and categorization) that provides a single result to indicate the level of sustainability of the built environment.
- In terms of impact on the community, the framework can potentially act as an education medium that encourages a continuous learning process, enhances communication between, and participation of the stakeholders Viz., Architects, Designers, Consultants, Engineers, Contractors, Suppliers, and Academicians. The framework developed could potentially be used as a guideline for planning or policymaking to promote sustainable

buildings in India. It is hoped that in this manner, the theoretical model becomes more flexible and consequently more adoptable, for other developing countries also.

More broadly, Sustainable Building Assessment Tool (SBAT) contributes to the development of a new model or approach appropriate to developing countries, through which a country-specific building sustainability assessment framework may be established.

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ABBREVATIONS

AHP	Analytical Hierarchy Process
ASHRAE	American Society Of Heating, Refrigerating And Air-Conditioning Engineers
BREEAM	Building Research Establishment Environmental Assessment Method
CC	Composite Cement
CASBEE	Comprehensive Assessment System For Built Environment Efficiency
CSS	Cascading Style Sheets
DEMATEL	Decision Making Trial And Evaluation Laboratory
DT	Delphi Technique
ELECTRE	Elimination And Choice Corresponding To Reality
TERI	The Energy Resources Institute
TBL	Triple-Bottom-Line
QBL	Quadruaple Bottom Line
SEET	Social, Environmental, Economic And Technological
LEED	Leadership In Energy And Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
GRIHA	Green Rating For Integrated Habitat Assessment
IGBC	*Indian Green Building Council*
MCDM	Multi-Criteria Decision Making
PROMOTHEE	Preference Ranking Organization Method For Enrichment Evaluation
EE	Energy Efficiency
EFTOPSIS	Entropy-Based Fuzzy Technique For Order Preference By Similarity To Ideal Solution
ELECTRE	Elimination And Choice Corresponding To Reality
FAHP	Fuzzy Analytical Hierarchy Process

GP	Geopolymer
GUI	Graphical User Interface
HTML	Hypertext Markup Language
JSP	Java Server Pages
M	Management
OPC	Ordinary Portland Cement
PPC-F	Portland Pozzolona Cement Fly Ash Based
PPC-S	Portland Pozzolona Cement Slag Based
RII	Relative Importance Index
RIP	Relative Importance Percentage
SBAT	Sustainable Building Assessment Tool
SBPS	Sustainable Building Performance Score
SMPI	Sustainable Material Performance Indices
SS	Sustainable Sites
SW	Social Welfare
T	Transportation
TOPSIS	The Technique For Order Of Preference By Similarity To Ideal Solution
WE	Water Efficiency

CHAPTER - 1

INTRODUCTION

1.0 General

The United Nations 2030 agenda on Sustainable Development goals are formulated to eradicate poverty, improve quality of education and reduce the impacts causing climate change (Allen et al. 2017). Due to this, every country shifted its focus on challenges and opportunities to address not only the environment dimension but also on the associated Social and Economic issues as well. The rapid increase in global warming and climate change cause Greenhouse Gas (GHG) emission; creating a necessity to act immediately to avoid hazardous consequences to future generations. The present chapter discusses the necessity of adopting sustainability, addressing the reasons behind the changes in climate, causes for depletion of natural resources, population, energy, water and waste generation. Further, due to rapid urbanization, the consequences the country is facing in the present scenario and the need for infrastructure development and their associated pollution and emissions are deliberated in understand the current scenario in India. The need for a shift from conventional construction practices to sustainable construction is briefly enunciated. The need for the technological indicator along with the existing social, economic and environmental indicators for achieving a sustainable building is brought forth by incorporating the concept of Reuse, Recycle, Reduce, Repair and Renovate (5R's). Also, the need for a new sustainable building assessment tool is addressed in detail keeping in view, the regional context, climate conditions, culture, heritage, and geographical conditions.

1.1 Research background

More than half of the world's population is in urban settings (Franco et al. 2017). According to the United Nations (UN) report, by the end of the year 2050 around 6.3 billion people globally are expected to live in the cities (Berardi, 2012, 2015a; Reddy, Raj, & Kumar, 2018; Tathagat & Dod, 2015). Due to this the urban inhabitants increase rapidly necessitating huge requirements of infrastructural facilities for transportation, housing, health, and education. This unintended population growth suffers from natural resource, energy consumption and pollution leading to environmental degradation

(Franco et al. 2017; Reddy, Kumar, & Raj, 2019a; Sharma & Gupta, 2016). Fig 1.1 shows the statistics of the growth of urbanization between 1970 and expectation in 2050. It is evident that beyond the year 2020, the percentage of urbanization and energy consumption demand increases asymptotically. The rapid growth in urbanization arises the need for additional infrastructure.

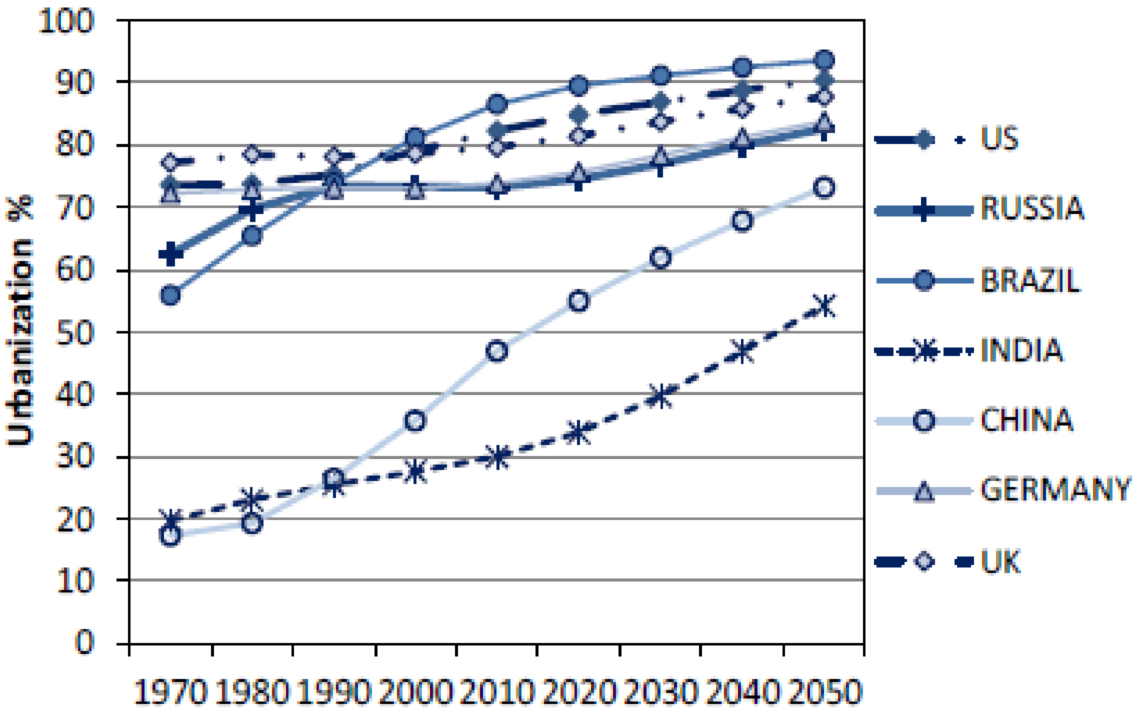


Fig. 1.1 Urbanization between 1970 and 2050 in various countries (**Source**: Berardi, 2015)

This year the Earth overshoot day was observed on 29th July 2019. This is the date on which human resources consumption exceeds the earth's generation capacity for the year (Fig. 1.2). Noticeably, it's been less than seven months we lost the earth's resource budget for the year 2019. This unplanned and rapid growth of urbanization and energy demand impends the unsustainable development, further leading to environmental degradation, social inequalities, and economic instability.

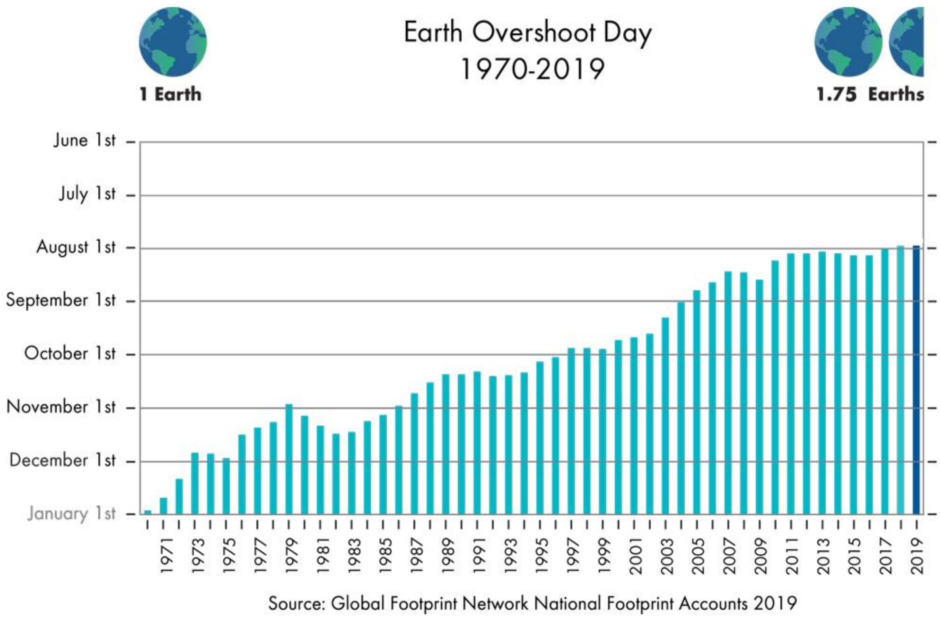


Fig. 1.2 Revolution of Earth Overshoot day
(**Source:** Tycho & Rebecca, 2019)

Owing to the part of urban dweller resource consumption, today's cities consume two-thirds of the world energy accounting to 70% of the Greenhouse Gas (GHG) emissions (McCormick et al. 2013). It is evident from Fig. 1.3 that compared to other countries, the emission of GHG is mainly from China and India.

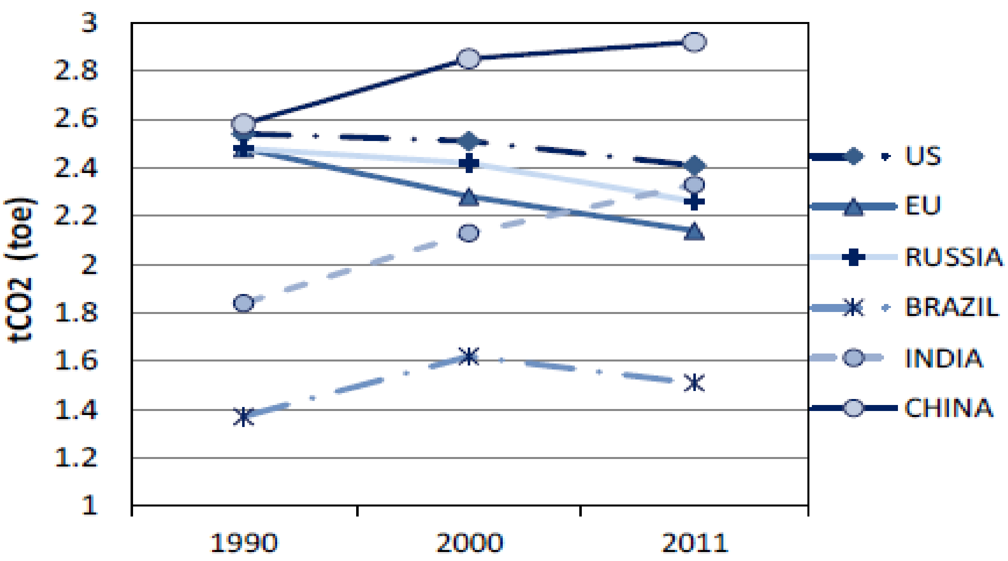


Fig. 1.3 CO_2 equivalent emissions per Primary energy supply (in a tonne of oil equivalent) in various countries
(Source: Berardi, 2015)

It is observed that the world's primary energy supply from various sources of mixed energies is growing its share day by day (Scutaru, 2013). Among them, it is predicted that oil and gas source account for 44% by the year 2050 (Berardi, 2015). By 2035, the gas source is likely to become the only energy source. Based on the Energy Transition Outlook 2018, fossil fuel consumption will reduce to 52% of the present consumption rate of 82% by the end of 2050. However, the peak demand for fossil fuels will occur in 2035 (Beddington, 2008) as shown in Fig 1.4 energy consumption is a serious consideration in many countries. Fig 1.5 shows Building energy consumption in various countries. According to The Energy Resources Institute (TERI), India needs vast measures on energy efficiency (Singh et al., 2016). Growing urbanization demand in developing countries like India is accompanied by a rapid increase in energy consumption and carbon emissions. In addition to this, the building sector accounts for 33% of total Indian energy consumption (Tycho & Rebecca, 2019). Unless specific policies are implemented, this energy demand will further increase to as high as five times by the year 2100 (Vyas & Jha, 2016). This arises the concern to take extraordinary measures to reduce energy consumption by various sectors, especially the construction industry.

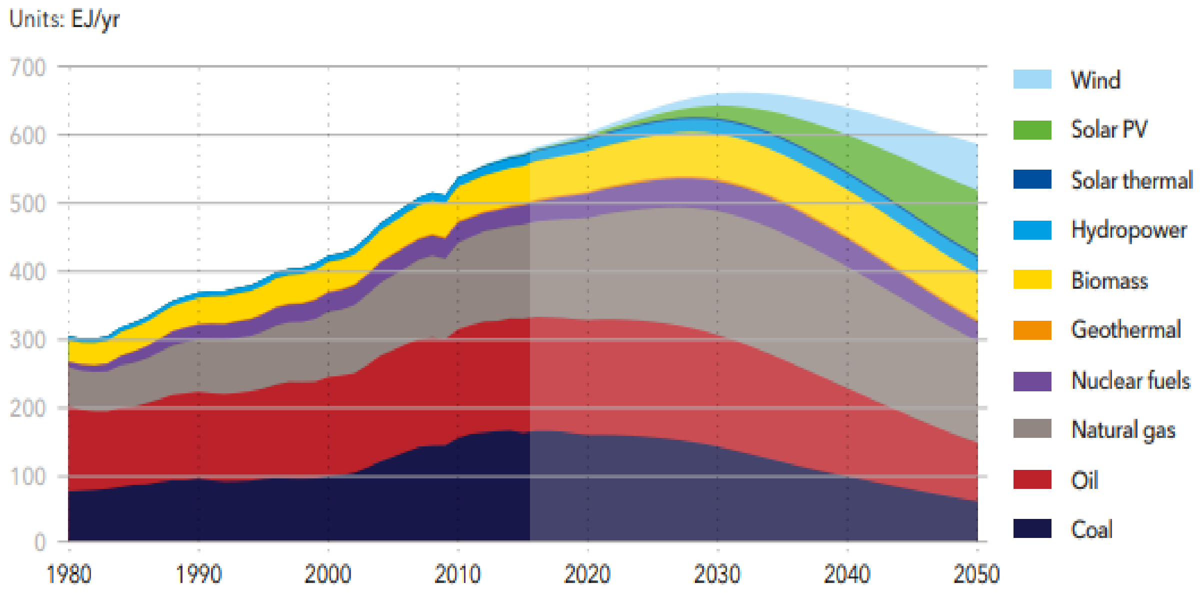


Fig. 1.4 World's Primary Energy supply by source
(**Source:** Energy Transition Outlook, 2018)

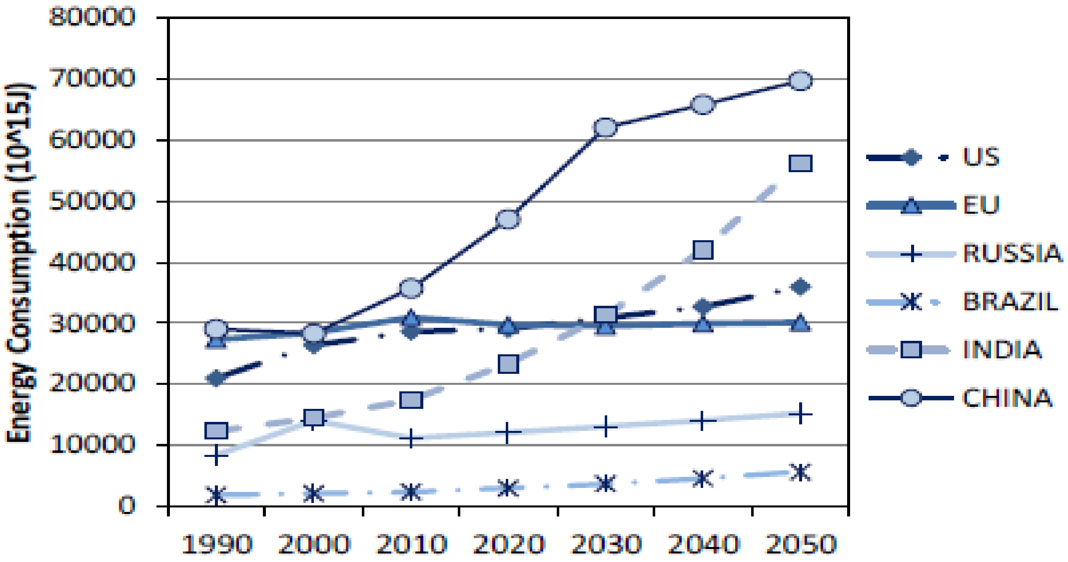


Fig. 1.5 Residual Building Energy consumption in various countries
(**Source**: Berardi, 2015)

India is the third-largest economy, second largest population and fourth largest energy consumption (Fig. 1.6). The acute problem of urban development in India will face monumental challenges (Smith, 2015). For this enormous growth in urban transformation in India, the only challenging solution for the present scenario is the paradigm shift in sustainable urban development.

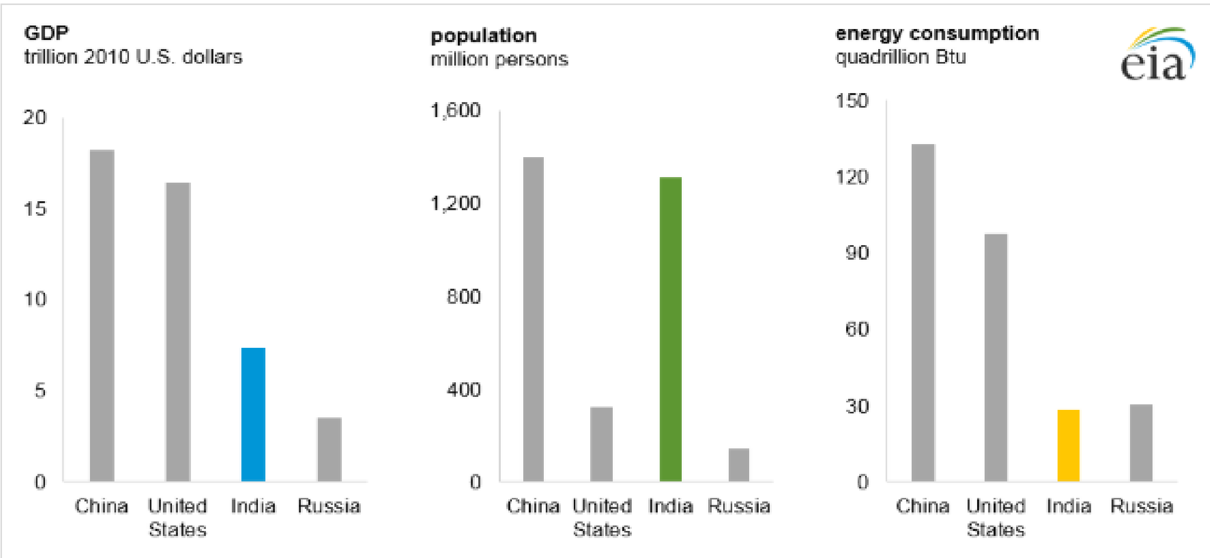


Fig. 1.6 GDP, Population and Energy consumption of different countries
(**Source:** https://www.eia.gov/outlooks/ieo/india/)

1.2 Sustainability in Built Environment

There are many definitions for sustainable development but the commonly known Brundtland report states ''*A development which meets the needs of the present without compromising the ability to achieve the needs of future generations*'' (Keeble, 1988). It assures to carry the on-going needs of present without depleting the natural or non-renewable resources for future needs. To bring this into practice, it is important to understand the concept of sustainability in different dimensions. According to Vanegas et al. (1996), sustainability is nothing but bringing human needs for a good quality of living without degrading the environment or interrupting the well-being of the people (Vanegas et al. 1996). To accomplish this, it is vital to understand the interrelationship between social needs, economic feasibility, and environmental impacts. The basic needs include the food, clothing & shelter and also all the ability to live at higher standards i.e., economical aspects. Therefore, promoting and incorporating sustainability is nothing but balancing the main three pillars ecologically, termed as sustainable development and this approach is known to be 'Triple Bottom Line' (TBL) approach. The World Resources Institute (WRI) acknowledges sustainable development as a difficult, confusing and even controversial concept (Hiremath et al. 2013; Illankoon, Tam, & Le, 2017; UNFPA, 2007).

The built environment was recognized as the largest contributor to changes in the environment (IPCC, 2007). The construction, operation, and maintenance of buildings are estimated to account for approximately 40%–50% of all energy usage and emissions of GHG globally (Dixit, 2017; Ponnada, 2015). There may be economic benefits from the investments in infrastructural projects, but they do cause more negative impacts on social and environmental issues. The United Nations defined sustainable construction as, ''*A holistic process looking to recover and keep harmony between the natural and built environment and to create habitability conditions that confirm the human dignity and encourage the social and economic equity*'' (United Nations, 2017). From the construction industry perspective, it is believed that sustainability should take into account the protection of a regional uniqueness incorporating localized architecture depending upon the local needs and objectives of the people despite their economic status (Ubarte & Kaplinski, 2016). It is understood that the sustainability in construction industry refers to habitat comfort, the durability and service life of the structure, optimum utilization of resources, efficient utilization of energy, water, land, protection of the environment, and developing social integrity.

The consumption of heavy natural resources for building construction mainly accounts for land use, water use and emission of pollutants and waste (Hongxun Liu & Lin, 2016). The only way of addressing these concerns is by adopting sustainable principles and designs in building construction. This study refers to the opportunity to assess building performance and ensure the implementation of sustainable design principles. It is significant to consider environmental, social, and economic dimensions (TBL approach) while assessing the building performance towards sustainability. However, the TBL approach has its own limitations as not all local-level development issues are clearly either environmental, social, or economic (ALwaer & Clements-Croome, 2010a, 2010b; Anadon et al. 2016; Cancino et al. 2015; Chan & Chan, 2004; Kaya & Kahraman, 2014; Kulkarni, Jirage, & Anil, 2017; Liu & Lin, 2016; Mahmoudkelaye et al. 2017; Teplý, Vymazal, & Rovnaníková, 2018).

According to PricewaterhouseCoopers (PwC) global construction 2025 report, the construction output will increase by more than 70% globally. This sudden growth, which is improving faster than that of global GDP, will be concentrated in three countries: China, the US, and India (Patil, Tharun, & Laishram, 2016). India will leave behind Japan as the third-largest construction market with average annual growth of 7.4% and it is expected to exceed China. It is also expected that by 2050, there will be an additional two billion inhabitants. So, the infrastructure development will be a major challenge (Andrew, 2017). Therefore, efforts are to be made to discover innovative products and solutions for building sustainable cities. Urbanization in India is increasing rapidly by maximizing the negative impacts on the environment. Indian carbon emissions are mainly from coal combustion, which shares up to 72% of all sources, and has a very less renewable energy source for energy production. The GHG emissions in India are increasing drastically, but compared to other countries, India seems to be performing better. (Fig. 1.7). However, due to rapid urbanization, the emissions may further increase beyond the expectation (Olivier & Schure, 2017)

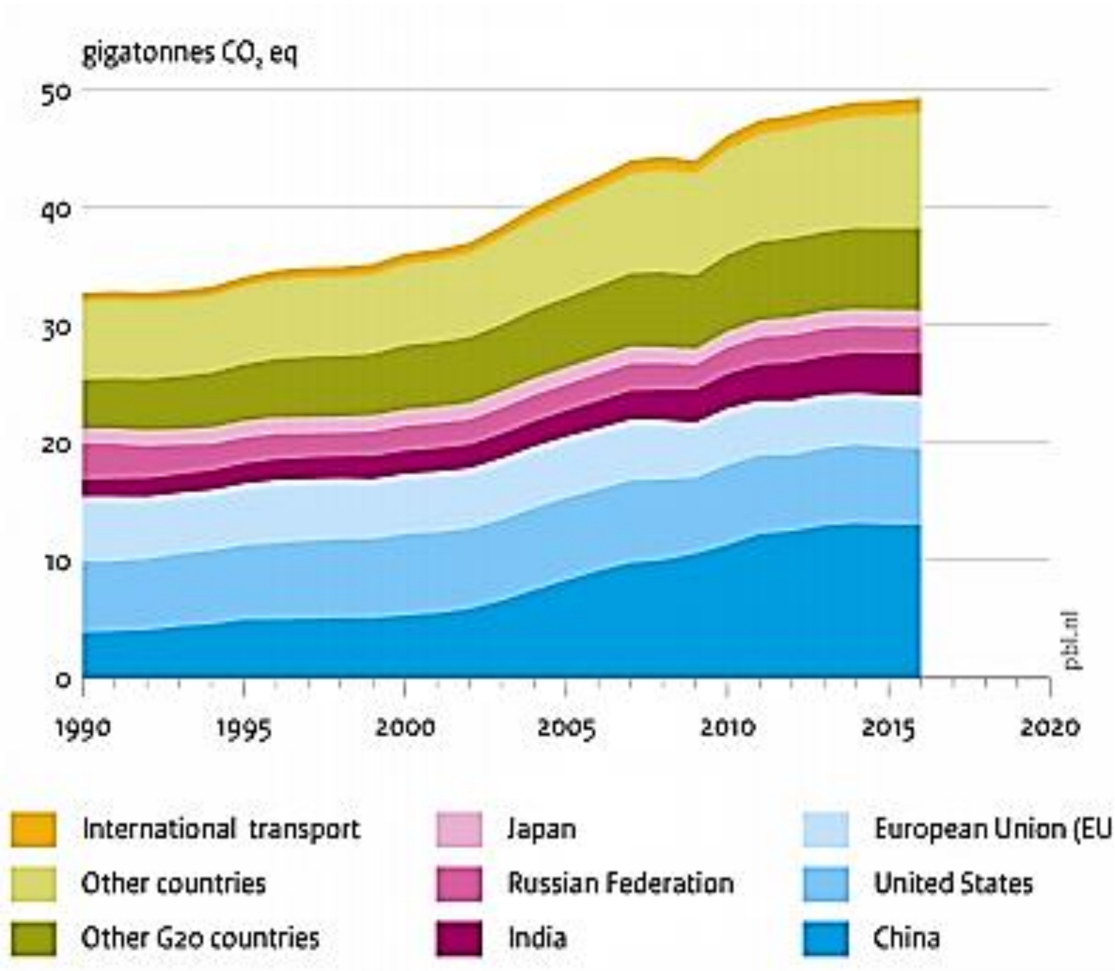


Fig. 1.7 Greenhouse Gas emissions of various countries

The UN " State of World Population Report" states that by the end of the year 2030, Indian urbanization will be increased to 40.8% (UNFPA, 2007). The total energy demand for India by 2047 is estimated to be 18,125 TWh of which, buildings account for 2,287 TWh (Fig. 1.8). This huge requirement of energy production leads to depletion of natural fossil fuels.

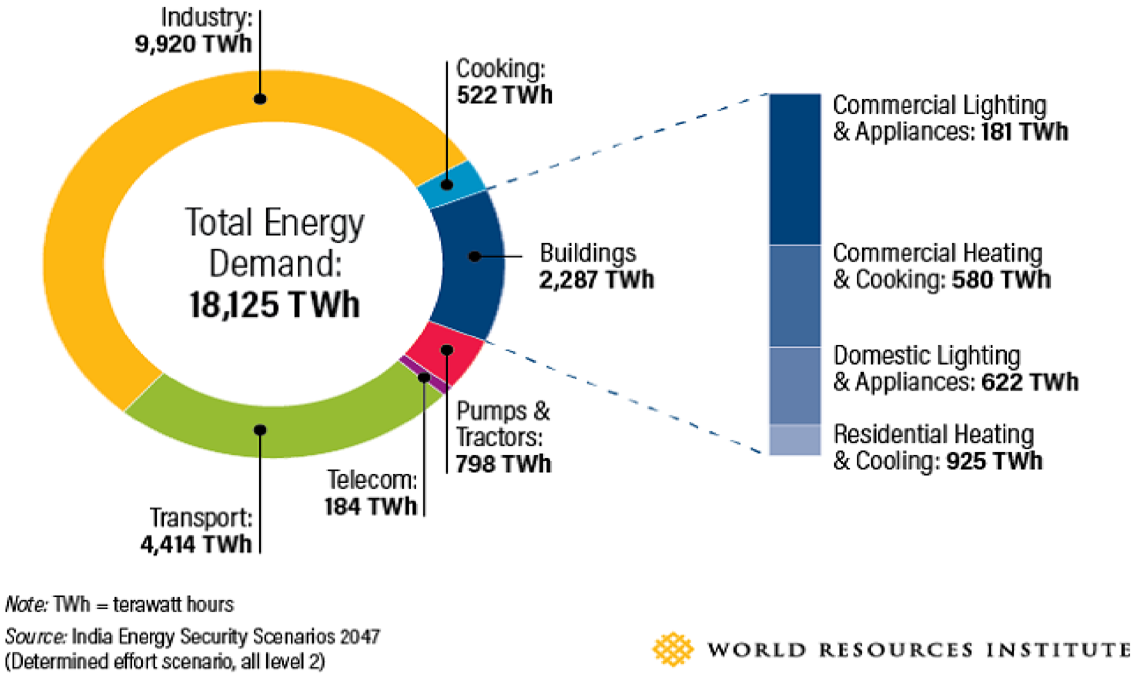


Fig. 1.8 India's Projected Energy Demand by 2047
(**Source:** India Energy Security Scenarios 2047, WRI)

India will be the third-largest global construction market after China and the US (Khatri et. al. 2011). At this growth rate in the next 10 years, India will be using huge material resources at a much faster rate than they have ever been used. In the recent past, Government of India has implemented the development plans and concept of smart cities, which can also contribute to ecological imbalance and carbon footprint either directly or indirectly. There are also efforts to look into every possible way to boost up the infrastructure development, for instance, in 12th Five Year Plan (FYP) Indian Government has allocated 9% of the Gross Domestic Product to infrastructure developments and the National Planning commission estimated an allocation of one trillion US $ for the next five years (Tathagat & Dod, 2015) with specific focus on urban transformation like development of Smart City Mission, Atal Mission for Rejuvenation and Urban Transformation (AMRUT), and Heritage Cities Development and Augmentation Yojana (HRIDAY), which can mainly boost the construction sector (Singh et al., 2016). This fast pace of growth in building infrastructure may lead to environmental degradation and can affect the ecological balance. This shows the urgency for promoting and implementing sustainable principles and practices. So, there is every need to reduce environmental impact and climate change for a better living world. This need can be fulfilled by introducing the concept of 5R's - Reduce, Replace, Reuse, Repair and Renovate (Vyas & Jha, 2016; Reddy et al. 2019a). For instance, Indian demolition waste constitutes more than 30% of total solid waste. The annual construction and demolition is estimated at 10 to 12 million tons in India (Ram & Kalidindi, 2017). Due to this, GHG emissions and other toxic material will deteriorate the health of people and the environment. Further, the raw material extraction, manufacturing, and transportation will damage the natural environment conditions. All these problems need to be addressed immediately to tackle the global issues of global warming, pollution, carbon footprint, and natural resource depletion.

According to report of Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Overseas Development Institute (ODI), under the umbrella of the Economic Policy Forum (EPF) supported by the German Ministry for Economic Cooperation and Development (BMZ) on “Promoting sustainable and inclusive growth in emerging economies: Green Buildings”, it was acknowledged that developing countries need further action and development in three broad areas:

1) Policy and regulation: strengthen the regulatory authorities and reinforcing the existing laws,
2) Capacity and skills: Lack of technical skill for the construction process, and
3) Awareness and understanding of benefits: Lack of awareness towards sustainability/green practices and their benefits (Economic Policy Forum, 2014).

Bebbington and others (2007), specified that “there exists a widely recognized need for individuals, organizations, and societies to find models, metrics, and tools for articulating the extent to which, and the ways in which, current activities are unsustainable”. Hence, it is understood that there is an overarching necessity to explore how to measure building performance to achieve sustainability in the construction industry.

1.2 Need for Sustainable Indicators and Criteria

A building construction project is considered as sustainable only when all the indicators of sustainability are taken into account. It is important to note that Sustainable/Green building is designed to minimize the environmental impacts and optimize resource consumption during various stages of its life cycle (Villarinho & Haddad, 2013). This focusses on implementation and adoption of sustainable building to monitor the performance and necessitates the identification of specific indicators and criteria to develop a building assessment framework. It is to be noted that, mere transfer of indicators and criteria from an existing building assessment framework developed in a particular country fails to incorporate the regional context, culture, heritage and geographical conditions of other country (Ali & Al Nsairat, 2009; Patil et al. 2016; Reddy et al. 2018). This Transfer of Technology will be successful only when current priorities and prevailing conditions of specific location are incorporated in it. The assessment tool developed for one nation or region will not suit another region. Thus, the development of building assessment tool based on criteria and indicators requires the active participation of experts from various domains of construction industry to consider real-time conditions of a specific region.

1.3 Need for Quadruple Bottom Line approach

Most of the building assessment studies are oriented towards environmental indicator only (Abdul-Rahman et al. 2016; Banani et al. 2016; Chan & Chan, 2004; Ding, 2008; Giddings, Hopwood, & O'Brien, 2002; Jamilus, Ismail, & Aftab, 2013; Riffat, Powell, & Aydin, 2016; Vatalis et al. 2013; Waris et al. 2014). This indicates disregard to social and economic aspects of sustainability, which could further lead to ecological imbalance and thereby, miss the real goal of sustainable development. While, some of them focused on measuring sustainable performance considering one or more indicators (Kylili et al. 2016), the criteria like energy efficiency, indoor air quality, water efficiency, water management, pollution, sustainable sites, human comfort, innovation, material efficiency, and renewable energy etc in most of the studies have assumed to be oriented towards only one or more indicators like environmental, cultural, institutional, social-economic or political etc., and ignore the significance of the same over other indicators. For example, the 'pollution' criteria considered under 'Environmental' indicator is presumed to be insignificant towards another indicator like social and economic indicators and evaluated the criteria measure towards sustainability. This means that the inter-relationship between indicators, criteria, and interdependency among criteria and indicators has been neglected. Few of them considered TBL approach but failed to incorporate the technological advances (Akizu-gardoki et al. 2018; Al-Jebouri et al. 2017; Ghodoosi & Eng, 2018; Laedre et al. 2015; Patil et al. 2016) which have always been the cornerstone in mitigating the unavoidable side-effects of development and in surpassing the limits/constraints dictated by the other indicators of sustainability (Park, Yoon, & Kim, 2017). Thus, it is imperative to incorporate the Technological indicator by rejuvenating ideas of 5R's into implementable solutions. The holistic view under the main umbrella i.e. TBL along with Technological indicator will balance the construction eco-system for achieving sustainability through Quadruaple Bottom Line (QBL) approach. Thus, there arises a need to integrate Social, Environmental, Economic and Technological (SEET) indicators in assessing the sustainability of building construction (Fig. 1.9). In this regard, the sustainable construction necessitates a building to be the most economical, socially viable, technologically feasible and environmentally friendly.

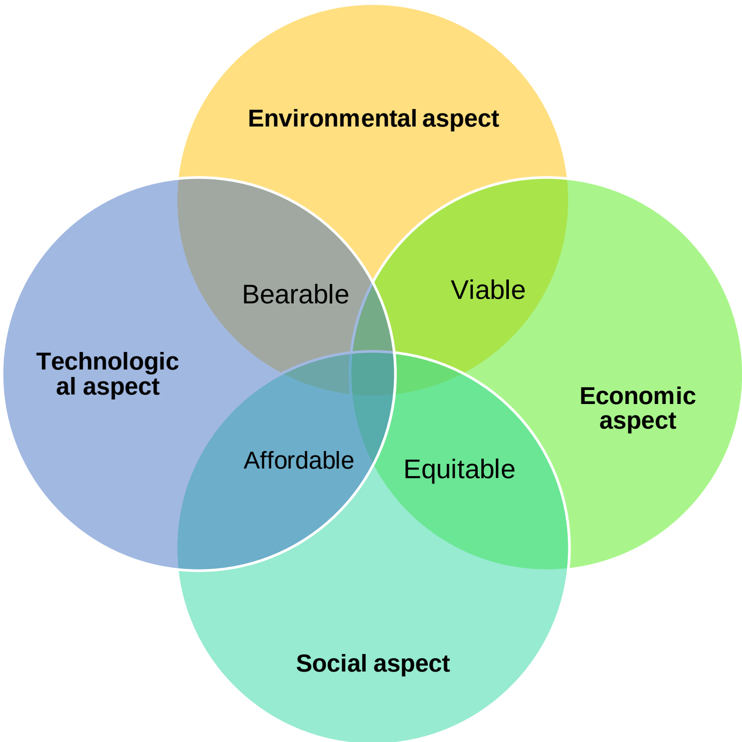


Fig. 1.9 Quadruple Bottom Line (QBL) approach

1.4 Need for developing a new building assessment tool in India

The existing building assessment tools considered various indicators and criteria for evaluating the building performance, and have been unsuccessful in suggesting the key sustainable indicators (Berardi, 2012). The models available for developing countries are inadequate for achieving sustainability in the construction industry. However, presently, there are no specific assessment tools that encompasses the Social, Environmental, Economic, and Technological (SEET) indicators to assess the building performance.

According to special Agenda 21, in developing countries like India, to create a sustainable built environment, it is required to progress in a different approach, unlike how the developed countries are working (Patil et al. 2016). There exists a cultural, ethical and economic dissimilarity between the developed and developing countries to understand and implement the sustainability in the construction industry. In comparison to developed countries, the transformation of traditional construction to sustainable construction is vigorous in developing countries, which have got a new trend in accepting the sustainable building guidelines (Magent et al, 2009). The existing building assessment tools like LEED, BREEAM, CASBEE, and GRIHA, and IGBC in India, have a lot of dissimilarities and some specific criteria which are required for Indian context are neglected. Some of the indicators which contribute to building sustainability are neither included in IGBC nor GRIHA. Similarly, the indicators which are included in IGBC are not included in GRIHA and vice-versa. For example, ventilation, CO_2 emissions, and material efficiency. Irrespective of these, some criteria like topographical consideration, climatic conditions, local context, and regional variations are not at all considered.

1.4.1. Overview of the Indian context

India is the seventh-largest country with an area of 32,87,263 sq.kms and lies on the India plate situated between 8°4' and 37°6' north latitude and 68°7' and 97°25' east longitude. It comprises of various climatic conditions across a wide range of topography, making it difficult to generalize. The Indian sub-continent has a great variation in temperature, humidity and precipitation distributions. It has six major climatic subtypes – Arid desert in the west, humid tropical in the Southwest, Alpine tundra and glaciers in the North and the island territories. The highest temperature ranges from 48°C - 51°C in Rajasthan and lowest ranges from -45°C to -20°C in Kashmir (Mehta & Porwal, 2013). It has rich bio-diversity, heritage, arts and architecture, and cultural history.

In India, water and air pollution are the major concerns. The source of pollution is through industrial, domestic, agricultural, and waste water. The untreated waste water is the major polluter of water pollution in rivers, lakes, and ponds. The combustion of fossil fuels is the major source for the release of airborne pollutants, GHG emissions, and harmful pollutants which affects the climate by increasing global warming. India is more vulnerable to climate change and socio-economic aspects due to rapid growth in urbanization and population (Lutz Meyer-Ohlendorf, 2019). The construction sector is the major contributor to GHG emissions. Due to the above consequences, there will be a huge demand for energy and water. According to the Intergovernmental Panel on Climate Change (IPCC) fourth report, there is every necessity to take appropriate efforts to reduce the carbon footprint from the building sector. It is required to shift from the conventional building technology to sustainable principles and techniques.

Indian construction exhibits a vernacular architecture, which is functional and purpose-oriented. The building of a particular location reflects the rich diversity of climate, local materials, local social customs, and craftsmanship. In addition to this, the regional variations in material usage can be observed in various locations - like in hilly regions, the rubble masonry, ashlar, and stone is used for the construction of walls. Similarly, wood beams and slate tiles are used to construct a roofing system. Pitched roof, bamboo poles with raised platform can be observed in the traditional vernacular system. On flat terrain, mud, soft stone and lime are used to construct the shelter (Pankaj khanna & kriti nagrath, 2011). All these materials are regionally available to sustain the prevailing climatic calamities and microclimate conditions at different locations of India. The technological aspects related to thermal comfort, earthquakes, lightweight materials, and efficient design strategies, etc, are interpreted from the past history of traditional building technology in India. There is a lot more information from the history and heritage of the construction technologies, which are still unknown to the world. These methods of designing and construction can cater to the needs of the growing demand for housing in urban areas wherever there is a shortage of land areas. With this, it is understood that materials play a vital role in the design of sustainable buildings. Accordingly, with these consequences and problems prevailing in India, there is an immediate need to shift to sustainable vernacular systems and practices into the modern arena by adding modern techniques and technologies. A new sustainable building assessment tool is required to improve the SEET indicators to evaluate building performance. It is crucial to understand the interrelationship between these indicators by considering regional context, climate, culture, heritage and geographical conditions in adopting the right assessment tool.

1.5 Research tools and Instruments

1.5.1 Delphi technique

The building assessment criteria involving multiple perception is considered to be a multi-dimensional approach (Grace K.C. Ding, 2008). To identify a comprehensive and effective criteria for developing a building assessment framework, a consensus based approach like Delphi Technique (DT) is required (Alyami & Rezgui, 2012; Chew et al. 2017), to critically identify and determine the applicable criteria for country specific location like India. In DT, the anonymous responses from the expert group will have an opportunity to reiterate the decision based on group communication and come out with a group agreement (Hsu, Chang, & Luo, 2017; Meiboudi et al. 2018; Okoli & Pawlowski, 2004).

1.5.2 Multi-Criteria Decision Making (MCDM) methods

MCDM refers to making decisions when multiple and conflicting criteria are involved. MCDM methods are being applied in different areas of engineering, science and human activities (Zavadskas & Durdyev, 2018). These methods can provide a solution to obtain the weights for criteria, including, Analytical Hierarchy Process (AHP) (Yoram and Saaty, 1980), Preference Ranking Organization Method for Enrichment Evaluation (PROMOTHEE) (Brussel, 1986), Elimination and choice corresponding to reality (ELECTRE) (Mousseau, Roy, & Paris-dauphine, 2005), etc. Among these, the quantitative and qualitative approach AHP is a simple and lucid way to obtain the interrelationship between various criteria and alternatives using pairwise comparison, where the problem is decomposed into a number of hierarchy levels to analyze them independently. This method has an inherent ability to deal with decision-makers judgments. However, it is incapable to handle the uncertainty and imprecision of the decision. Fuzzy set theory is integrated with AHP to capture the vagueness, uncertainty, and imprecision of the decision-maker. This integrated Hybrid MCDM technique can be utilized to obtain the relative weights of criteria and alternative for any given problem involved with a number of decision-makers.

1.6 Sustainable Material Performance Index

India is a country with a fast-growing economy in the world (Dhull, 2018). The development and sustainability should go hand in hand to maintain global ecological balance. The green practices are in action to reduce the overall CO_2 emissions and are being implemented in the construction industry. Sustainable principles practices and selection of suitable building materials play a vital role in achieving sustainable construction. Use of correct materials could reduce carbon emissions to 30% (González & García Navarro, 2006) and unless the action for sustainable material consumption and implementation are enforced, energy consumption, waste, and Greenhouse Gas (GHG) emissions continue to grow further.

Due to the availability of different material alternatives in the market, the practitioners are facing difficulty in choosing the right material for what they are intended. For a given application, various material alternatives are available, each of them have their own characteristic properties, advantages, and constraints. Understanding the functional requirements and considering the influence of significant factors and criteria, simplifies the problem of selecting a particular material for a given application.

Issues like pollution impact of materials, material depletion potential, recycling capability, reusing capability, energy consumption, waste production, low maintenance, and economical material are important issues to be considered for sustainability. Selecting an appropriate material, considering, many factors and conflicting criteria is a complex MCDM problem, challenging enough to evaluate alternatives involving subjective and objective criteria.

Potential sustainable building materials are based on three sustainability criteria: environmental, social and economic. To design the product for our specific needs using 5R’s, it is also important to find their technological properties as well as sustainability indicators (Bakhoum & Brown 2012; Bank et al. 2011; Kisku et al. 2017). The strategies to enhance sustainability is country-specific and depends on its size, culture, and economic position (Šaparauskas & Turskis, 2006). For example, Al-Hajj & Hamani (2011), Govindan (2015) & Radhi (2010) in UAE, Wang et al. (2018) in Taipei, Ejiga (2017) in Lagos, Abeysundara (2009) in Srilanka, Akadiri (2012) and Bakhoum & Brown (2015) in UK have studied the country-specific parameters for assessing and selecting sustainable construction materials.

Sustainable material performance is assessed based on specific parameters in various life cycle stages i.e., extraction, transportation, manufacturing, maintenance, and demolition. All these stages require inputs (energy, water, and land) producing outputs (emissions and waste). The detailed track of inputs and outputs in the multi-step process (Goal and Scope, Inventory analysis, Impact assessment, and Interpretation) to assess the environmental impacts is known as Life Cycle Assessment (LCA). The portion of data collection for inputs and outputs for a particular functional parameter is a repository database called a Life Cycle Inventory (LCI) data. Developing inventory data is the most difficult and time-consuming process. The inventory data developed for one nation cannot be utilized for others (Curran, 2012; Reap et al. 2008). In developed countries, the availability of material inventory data on environmental impacts throughout their lifecycle makes the material evaluation approach versatile (Cole, 2005). There are several LCA based tools specific to a location like ATHENA in North America, ENVEST in the UK. Every tool will be using the embodied Life Cycle Inventory (LCI) data to find the impacts of the materials (Trusty, Horst, & Horst, 2002).

In developing countries like India, due to the availability of limited LCI data, it becomes difficult to analyze the material performance towards the environment. Also, LCA is a time-consuming process and does not consider socio-economic and technological impacts throughout the material lifecycle. Hojjati (2017), opines that it may not be an appropriate approach for assessing the material in terms of environmental impacts alone in developing countries like India. Hence, this necessitates selecting a material alternative based on sustainable indicators factors, material lifecycle phase to reduce the environmental impacts, improve social well-being, improve economic viability and ensure technological feasibility for achieving sustainability.

1.7 Graphical User Interface (GUI) and QR code

For fast and intuitive calculations of logics and generic algorithms, human knowledge is not sufficient to get the desired output GUI constructs the time sensitive service to the user to facilitate quick decision. The representation of graphics in different forms enable the user to interpret the data effectively (Kokalj, 2003). The GUI tool integrates the techniques and evaluate ready-made solutions in the form of pleasing pictorial representation (Hensen, 2004; Winograd, 1995). This enables the users to easily operate cumbersome calculations with high degree of precision within less time.

1.8 Summary

In the present chapter, the importance of sustainability in construction industry is discussed. The indicators and criteria influencing the sustainable construction and measurement of performance of building towards sustainability is highlighted.

Technological indicator along with the existing indicators in TBL approach is introduced to rejuvenate ideas of Reuse, Recycle, Replace, Repair and Renovate (5R's) into implementable solutions. The importance of material performance over building sustainability was discussed. Also, the requirement of new building assessment in developing countries like India is addressed. A brief introduction to research tools like DT and Fuzzy AHP is discussed. The requirement to develop QR code based GUI for evaluating the building sustainability is highlighted. Based on these different areas identified, a critical review of various literature works was taken up and is presented in Chapter 2.0.

CHAPTER – 2

LITERATURE REVIEW

2.0 General

In the previous chapter, the causes for over-exploitation of natural resources and impact on the environment was highlighted. The future requirements for energy production and renewable resources was also discussed. The need for switching from conventional construction practices to sustainable principles and practices was discussed. The importance of material performance over building assessment was also brought out in the previous Chapter. The overarching necessity to measure building performance to achieve sustainability in developing countries like India was addressed. In the present chapter, a review of literature related to sustainable construction, sustainable criteria and indicators influencing sustainable construction is addressed with an extension to existing building assessment tools. The importance of exploratory studies to establish priorities and finding significant insight into making decisions is discussed. The building assessment tools like LEED in US, BREEAM in UK, along with the Indian building assessment tools including GRIHA are deliberated in this chapter. The studies associated with the influence of construction material over building performance for achieving sustainability is addressed. Further, the significance of Multi-Criteria Decision Making (MCDM) methods to measure sustainable material and building performance is discussed. Finally, the literature related to development of Graphical User Interface (GUI) attempted by previous researchers is reported.

2.1 Review of literature on sustainable construction

Sustainable construction can be well-defined as a construction practice which incorporates elementary goals of sustainable development (Cole, 2005). Kibert & Kibert (2003) depicts the relative importance of building life cycle stages and their resource requirements, emissions, and waste. It was opined that the ecosystem integrated with buildings will enhance the quality of living, leading to Bio-Urbanism. This study also observed the development and implementation of Building Information Modelling (BIM) tools like BEES (US) and ATHENA (Canada) in simulating the building performance. The advanced engineering tools like energy modelling for energy flow, Computational Fluid Dynamics (CFD) for air ventilation, passive heating and cooling and radiant cooling came into use. The study reveals that sustainable alternative is a function of age and income and 90% of the higher income group in US are willing to opt for green building benefits. This study also observed that there were substantial changes in devoting sustainable construction concepts for the past one decade and need a mile long way to achieve sustainability based on renewable resources only.

The work of Yasuyoshi Miyatake (1996), addressed a comprehensive perception of sustainable construction and the role of technology in achieving sustainable construction. From this study, it was realized that the three ways of achieving sustainable construction can be through 1) Creating built environments by changing the process of construction from linear to cyclical. This can be achieved with the concept of recycle, renew and reuse of materials. 2) Restoring polluted environments through engineering practices by treating soil, air and water free of contaminants and pollutants using latest technologies. This is the area of advancement in environmental engineering and technology. 3) Improving arid areas like barren lands, deserts, and unused and making them habitat for flora & fauna and humans.

Lue Bourdeau (1999) focused on the relationship between construction industry and principles of sustainable development. An exploratory study was performed on the understanding of sustainable construction defined by various countries through brainstorming, interviews, and questionnaire surveys, and observed that, the principles and goals proposed does not suit necessarily the concept of other countries. To address this issue, it was suggested to incorporate the possible dimensions to each country as they needed. It was also suggested that poverty, population, density, underdevelopment, national economy, standard of living, availability of land, geographical features, energy production and design of building construction influence the interpretation of their own country's dimensions. The findings of this study also reveal the barriers for not achieving sustainable construction which includes physical problems of resources, biological problems related to human needs, and socio-economic aspects.

Raynsford (2000), states that sustainable construction improves the quality of human life and habitat satisfaction supporting the social and environmental desires for the future generations. The study emphasized on the UK government's role in making policies, strategies and legislative framework to improve the sustainability and recommended that, government play a vital role in achieving sustainable construction by drawing down the clear cut policies and regulations. For this, approved guidelines and documents support the principal aspects of sustainable construction in framing the policies and guidelines. This study concludes that the Government has to aim at strategic planning to contribute to the sustainable development not only in construction stage but also in operation, maintenance and improvement stages of the building.

Kibert (2003), observed the state of sustainable construction after one decade of its initialization of movement for sustainable development. The study reviewed papers related to sustainable construction and acknowledged the challenges, current developments, opportunities, obstacles and concerns.

Du Plessis (2007), in his paper addressed means to implement the challenges raised by Agenda 21 for sustainable construction reported by International Council for Research and Innovation in Building and Construction in 1999. CIB is treated as the mediator between international and national agenda on sustainable construction for developing countries. It provides common concerns, issues, challenges and barriers and opportunities considering national and local priorities. The goal is to achieve global interventions for sustainable construction agenda by providing adequate shelter, clean water, sanitation, energy and food. It was postulated that sustainable development not only depends on three pillars of development – social, environment and economy but also adds up the pillars for political, cultural, institutional and technical. It was mentioned that achieving sustainability not only lies in actions with respect to three pillars but in relationships between them, which is a holistic solution to interdependent relationship between humans, society, economy and technology and the biosphere (Zavadskas, 2018).

To enable sustainable construction in developing countries it is necessary to think from part to whole i.e., creating viable local construction sector and then ensure it responds to principles of sustainable development, which is possible only with the involvement of all the stakeholders' perceptions (Ferrer et al. 2018; Liu et al. 2014; Rohracher, 2010). The technological aspects relate to hardware technology – equipment, materials, infrastructure solutions, industrial processes; Software technology – models, tools, decision support systems, evaluation systems, and monitoring systems; Knowledge and information – guidelines and manuals, policies, benchmarks, and knowledge database systems. Further, to enable the technological transfer and functional institutional governance the study suggested some key areas of development and implementation as shown in Table 2.1. On the whole, this study has identified urgent actions to be implemented in the developing countries such as raising awareness, capacity building, building networks and partnerships, and information benchmarking.

Chatterjee (2009), opines that present human perception focused on the standard of living, instead of need and purpose. The paper suggests five facets which contribute to the sustainable construction in India. Firstly, the knowledge of interdependency that enlighten engineers on the demand and supply of energy and material flow for the present and future. Secondly, the knowledge of conservation and efficiency which clarifies that, matter and energy cannot be created nor destroyed and thus it should not be wasted. The third facet is on knowledge of surviving designs based on law of thermodynamics. The fourth facet of building ecology is the knowledge of natural systems which focusses on the diversity of ecosystem. The last facet, the knowledge of change, suggests that sustainable buildings are those which adapt to the change and are resilient to environmental conditions.

Table 2.1 Key areas for achieving sustainable construction in developing countries

Time	Technological	Institutional	Values
Immediate	• Benchmarking & Assessment • Knowledge systems & data-capturing	• Clarified roles and responsibilities • Education • Advocacy & awareness • Cooperation and partnership	• Mapping the route to change • Understanding the drivers • Re-evaluating heritage
Medium	• Technologies to mitigate impact	• Linking research to implementation • Develop regulatory mechanisms	• Develop a new way of measuring value and reward • Develop codes of conduct
Long term	• Technologies of the future • Changing the construction process	• Strengthening implementing mechanisms • Using institutions as drivers • Regional centres of excellence	• Corporate social responsibility reporting

Pitt et al. (2009), investigated the influence of supply and demand in realizing sustainability. Based on quantitative questionnaire survey, the drivers, barriers and benchmarking indicators were identified and measured. The findings revealed that the financial incentives and building regulation was observed to be an important driver in attaining sustainability in construction industry. Affordability is the biggest barrier in implementing sustainable principles. Lack of customer awareness will reduce the demand and influence on the client supply. This study has also observed that, to achieve sustainable construction, it is vital to bridge the gap with respect to the client's demand. Tan et al. (2011), suggested a framework for implementing sustainable construction practices to help contractors in meeting their competitive environment by implementing sustainable strategies. Based on a comprehensive review of studies carried out, it was observed that the sustainable performance of the building can improve the business competitiveness. Integrating sustainability aspects into the business can enhance long-run profitability and achieve continuous improvement. Based on this view, Ubarte & Kaplinski (2016) took a comprehensive review on sustainable built environment between 1998 and 2015. The following findings are observed from the study.

1) The interaction between the social, economic, institutional, cultural, and environmental aspects is considered as the backbone of sustainable construction, and the welfare of the society depends on the adoptability of sustainable construction.
2) The acceptance of new and innovative ideas is a challenge for urban development towards sustainability.
3) The need for Multi Criteria Decision Making (MCDM) methods is essential to measure the sustainable construction performance, in developing various frameworks.
4) It is felt that the well-known building assessment tools developed for country-specific frameworks are not suitable and applicable to the other countries. It is vital to evaluate the building performance considering surrounding morphology integrated with Building Information Modelling (BIM) with regard to local climatic variations.

Tudor et al. (2016) suggested that, in case of developing countries like India, for efficient utilization of resources, sustainable strategies are essential. It was observed that, in India, water and electricity are the major problems in the near future. Cities like Delhi and Chennai is expected to have water deficiency by 2020. It is also suggested that modelling various strategies requires public agreements within a spatial and temporal context. The study witnessed the influence of environment issues with respect to social aspects as recycling, pollution and climatic changes.

Verena Göswein et al. (2019) expressed that the classic Life Cycle Assessment (LCA) is suitable for accounting Environment impacts of technologies only. Instead, the study suggested the anticipatory LCA (a-LCA) to design the product to overcome the challenges of data availability, risk assessment, stakeholder involvement, and multi decision making. In the process of a-LCA, the data is collected from generic to site-specific along with scaling effects and market driven impacts. This approach improves the product eco-design through improved early detection and optimize material prioritization using local building codes, stakeholder perception and material supply chain so as to enable new developments in the areas of bio-based and phase-change material. Keeping in view these concerns, practices and problems, the conservation of electricity and water, lowering Greenhouse Gas (GHG) emissions, developing government policies and guidelines, community-wise initiatives, and awareness among the people are the five strategies in implementing sustainable practices in India.

From a broad review of literature on sustainable construction it clear that there is an imperative need to adopt and implement the strategies of sustainability in construction industry. Also, it was identified that Technological indicator along with Social, Environmental and Economic has significant impact in rejuvenating the ideas of 5R's into implementable solutions. Further, it was observed that significant criteria are to be identified for evaluating and monitoring sustainable construction practices in building infrastructure.

2.2 Review of literature on sustainable indicators and criteria

Toor & Ogunlana (2010), explores the importance of indicators from various stakeholders of construction industry to measure the performance of projects towards sustainability in Thailand. The study observed that the traditional measures are no more applicable for effective performance of the construction projects. The indicators safety, efficient resources, stakeholder perception, conflicts and disputes are predominant in large scale projects. The study also suggests that comprehensive project evaluation should not only consider quantitative objective criteria but also qualitative subjective criteria in meeting the future expectations and demands of stakeholders. Future expectations should be related to socio-economic, operational, strategical, and life cycle issues to meet the demands of sustainable construction.

Gilmour et al. (2011), developed a framework for the Dundee waterfront project to measure the sustainability in all stages of the construction work considering all the stakeholders involved in the project. Procedures including information flow diagram and decision flow maps to identify and categorize the indicators respectively were suggested. From the developed diagrams of information flow approach a high degree of public consensus was revealed. Similarly, based on decision mapping technique the real world applicability and its integration with society was observed.

Monfaredzadeh & Krueger (2015), opines that due to rapid advancement of the technology, the importance of social communities is neglected in development of a smart city. The study reveals the importance of public players to strengthen the social aspects in improving the quality of life.

Zhong & Wu (2015), analyzed the performance of reinforced concrete and Structural Steel (SS) framed buildings considering environmental, economic and constructability in Singapore. The study mainly concentrated on creating safety and health based on ecological design and resource efficiency. The results suggest that SS is expensive and is weak in preventing noise pollution and due to strict regulation policies in Singapore, construction safety and duration to construct is also limited. The Reinforced Concrete (RC) is superior than the SS framed building in terms of construction, maintenance and financial costs. But, SS framed building has outperformed with regard to recyclability, reduction in waste, water consumption, construction durability and quality.

Vyas & Jha (2016) studied the comparison of various existing building assessment tools (LEED, BREEAM, SB-Tool, LEED- India, CASBEE, Eco-housing, and GRIHA) and observed that there exists some differences and limitations in applying to the Indian context and necessitates a new building assessment tool development. Based on Principal Component Analysis (PCA), the indicators to evaluate the building performance are identified as environment, site selection, building resources, innovative techniques, building services and management, indoor air quality, and economy.

Teng et al. (2019) has developed a dynamic system to explore the driving forces using Statistical Package for Social Sciences (SPSS) and Advanced Mortar System (AMOS) to achieve the Sustainable Development of Green Building (SDGB). Also, Structural Equation Modelling (SEM) is utilized to model the dynamic interactions of driving forces considering the data collected from a structured questionnaire survey. The findings of the study revealed that market development towards environmental aspects, economic value, participation of stakeholders, and ecological importance are most significant impacts on sustainability. Similarly, Anadon et al. (2016), reveals the importance of Technological innovation to harness the action proposals in achieving sustainability along with socio-economic, cultural and environmental aspects. It is one of the Sustainable Development Goals (SDGs) to improve the human well-being. Table 2.2 shows the criteria that are mostly recognized by various researchers.

Table. 2.2 Prominent Criteria adopted by various researchers

Criteria	(Ali & Al Nsairat, 2009)	(Alyami & Rezgui, 2012)	Yu et al. (2015)	(Vyas & Jha, 2016)	(Banani et al. 2016)	(Zarghami et al. 2018)	Kamarizzaman et al. (2018)
	Jordan	**Saudi Arabia**	**China**	**India**	**Saudi Arabia**	**Iran**	**Malaysia**
Water	√	√	√	√	√	√	√
Indoor Air Quality	√	√	√	√	√	√	√
Materials	√	√	√	√	√	√	√
Energy	√	√	√	√	√	√	√
Waste	√	√		√	√		√
Transport			√				√
Management		√	√	√	√		√
Sustainable Site	√	√	√	√	√	√	√
Human Satisfaction	√	√	√	√	√	√	
Cultural Heritage		√			√		√
Quality of services		√			√		√
Health and Well-being	√	√	√	√	√	√	√
Flexibility and Practicability	√		√			√	

The various criteria adopted in the existing country specific building assessment tools are shown in Table. 2.3. According to Kylili et al. (2016), "*achieving sustainability through conservation, recycling and research and development of new materials and technologies is the next great challenge for civil engineering and construction industry."* Barbosa & Almeida (2017), reveals that most of the existing assessment tools are oriented towards environmental aspect alone and there is a need to integrate social, economic, cultural, institutional, and technological indicators in developing countries (Abdul-Rahman e tal. 2016; Banani et al. 2016; Chan & Chan, 2004; Grace K.C. Ding, 2008; Giddings, Hopwood, & O'Brien, 2002; Jamilus, Ismail, & Aftab, 2013; Riffat, Powell, & Aydin, 2016; Vatalis et al. 2013; Waris et al. 2014).

In today's modern world, technology is developing in every aspect of life; likewise technology has very high effect on construction industry (Darko & Chan, 2017; Du

Plessis, 2002). Modern innovative materials and technologies are playing a big role in reducing GHG Emissions; Construction waste; Minimizing energy and Water consumption etc., along with environmental, social, and economic indicators of sustainable development (Ferrer et al. 2018; Reddy, Kumar, & Raj, 2019a).

Most of the developed countries have created their own building assessment tool considering a number of indicators and criteria. Different assessment tools considered different criteria for evaluation of buildings, specific to locations (Alyami, Rezgui, & Kwan, 2015; Vyas & Jha, 2016). Some of the prominent and widely used building assessment tools are Leadership in Energy and Environmental Design (LEED) in US (Fig. 2.1), Building Research Establishment Environmental Assessment Method (BREEAM) in UK (Fig. 2.2), Green Rating for Integrated Habitat Assessment (GRIHA) in India (Fig.2.3), Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan etc.

Table. 2.3 Criteria adopted by various existing country specific building assessment tools

Criteria	GB CERTIFICATION SYSTEM	Management	Energy Efficiency	Indoor Environment Quality	Land use, Site and Ecology	Water Efficiency	Material & Resource	Emission and Pollution	Mobility and Transportation	Health and Well being	Economic	Cultural and Social	Innovation
Canada	Green Globe	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓
Colombia	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Brazil	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
US	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Dutch	BREEAM-NL	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
France	HQE	✓	✓	✓	✓	✓	×	✓	×	✓	×	×	×
German	DGNB	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	×
Espana	LEED	×	×	✓	×	×	✓	×	×	×	✓	✓	×
Polish	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
	EU GB												
Sweden	Eco Effect	×	×	×	×	×	✓	✓	×	✓	×	×	×
Turkish	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
	DGNB	×	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	×
UK	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
Emirates	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
	Estidama												
Jordan	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Australia	Green Star	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓
Indian	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
	LEED	×	✓	✓	✓	✓	✓	×	✓	✓	×	×	✓
	IGBC	✓	✓	✓	✓	✓	✓	×	✓	✓	×	×	✓
Japan	CASBEE	×	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓
Singapore	SGBC	×	✓	×	×	✓	✓	×	×	✓	×	×	✓
Hong-Kong	BEAM	×	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓
	BEAM PLUS	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓
New Zealand	Green Star NZ	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	✓
Malaysia	GBI	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Finland	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
Italia	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Panama	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Qatar	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
Russia	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
	BREEAM	✓	✓	×	✓	✓	✓	✓	✓	✓	×	×	✓
Serbia	LEED	×	✓	✓	✓	✓	✓	×	×	×	×	×	✓
Total		14	25	20	22	26	26	18	15	18	3	3	22

It is noteworthy to observe that, there are more than 28 building assessment tools in the world (Fig. 2.4), each one differs with the methodology, relative weight calculations, variations in climate, culture, geographical, local context and other regional variations. Several studies have attempted to compare these tools to identify the differences and similarities in them (Banani et al. 2016; Korkmaz et al. 2009; Mattoni et al. 2018; Reddy, Raj, & Kumar, 2018). Most of the assessment tools lack the consensuses in identifying and assigning weights to the criteria. Each tool vary by their adopted indicators, criteria, sub-criteria/attributes, relative weighting process, and assessment method. Due to variations in climate, region culture, geographical, and local context these tools are not completely transferrable and adoptable to other countries (Alyami et al., 2015; Kylili & Fokaides, 2017). In addition to this, these assessment tools lack the global sustainable indicators, criteria and attributes so as to make consistent assessment and compare among different locations. Further, it becomes very difficult in developing countries like India, which has diversified circumstances with respect to climate, culture, heritage, topography and regional variations (Al-Jebouri et al. 2017; Reddy et al. 2018; Sev, 2011). To evaluate the building performance calculation, tools like LEED, Green building Index, and HK BEAM have direct/simple summation of achieved credit points, while BREEAM is based on weighted sum credit model, and few of them like CASBEE is based on the ratio between achieved credits points to environmental loading. But, the unique thing which was observed in all tools is the hierarchy structure of evaluating the relative weights.

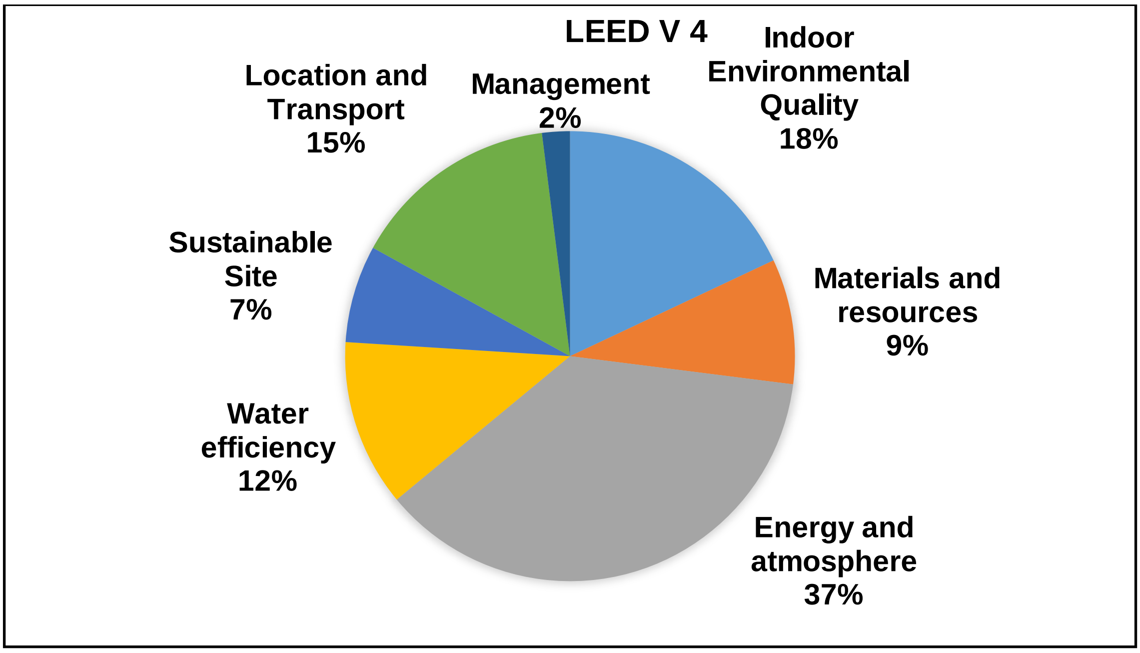


Fig. 2.1 LEED V.4 rating system with relative weights to criteria

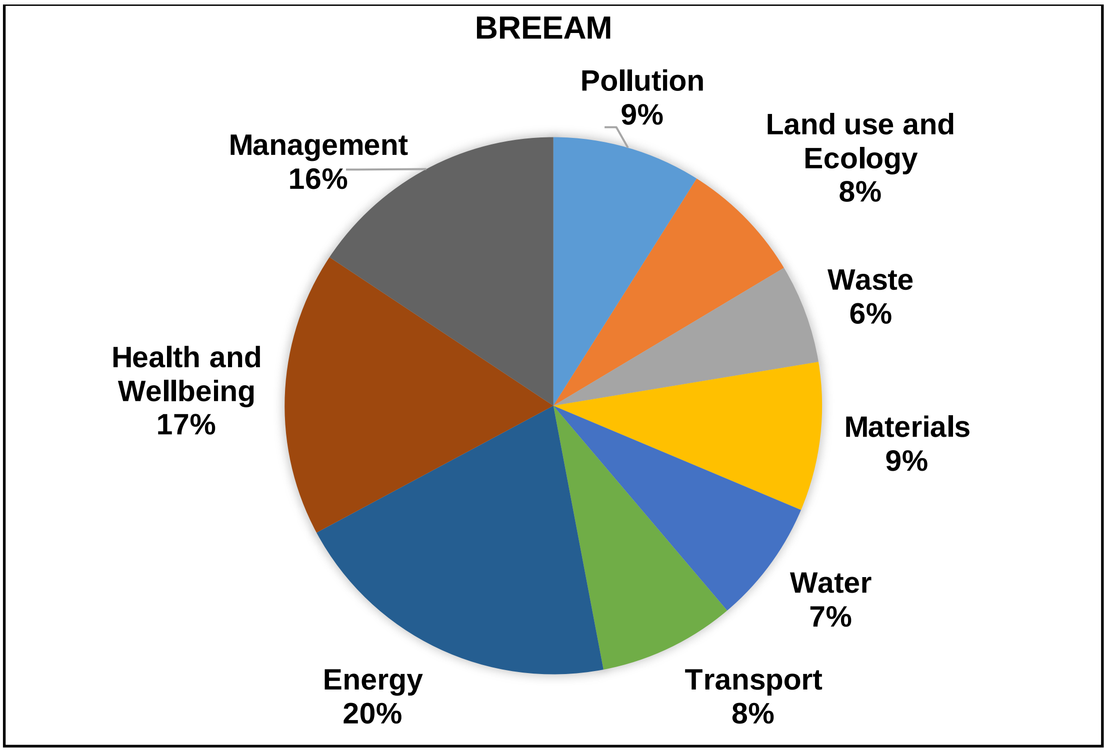


Fig. 2.2 BREEAM rating system with relative weights to criteria

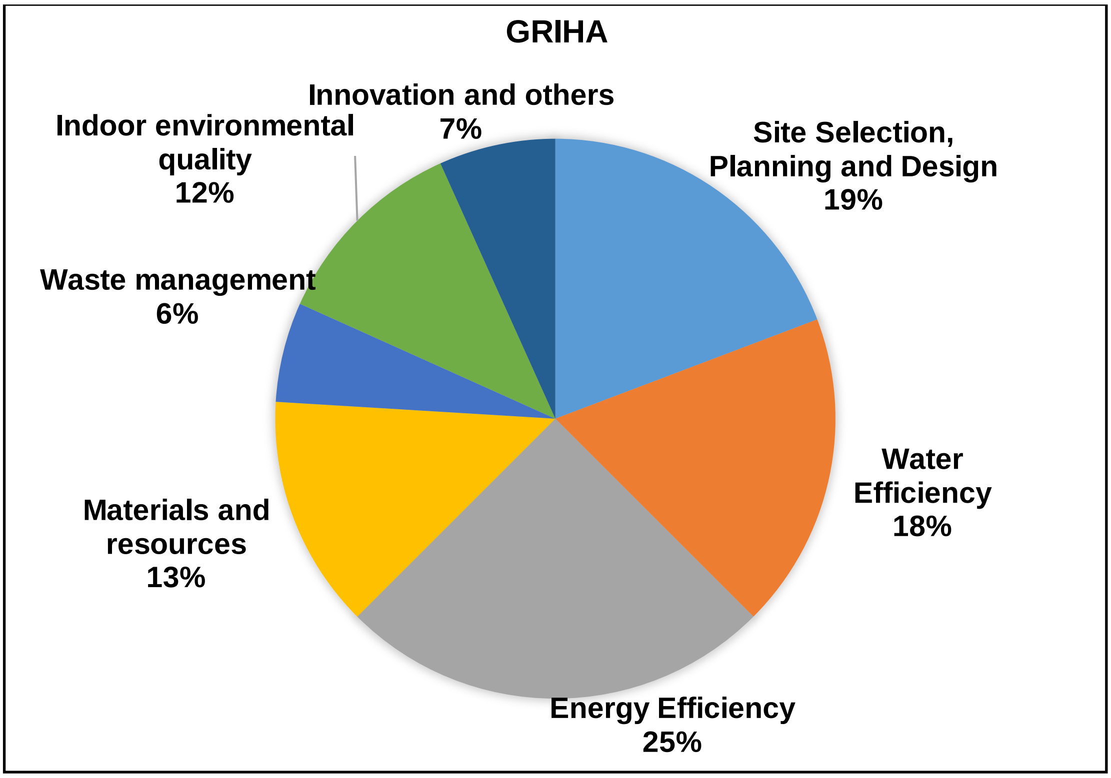


Fig. 2.3 GRIHA rating system with relative weights to criteria

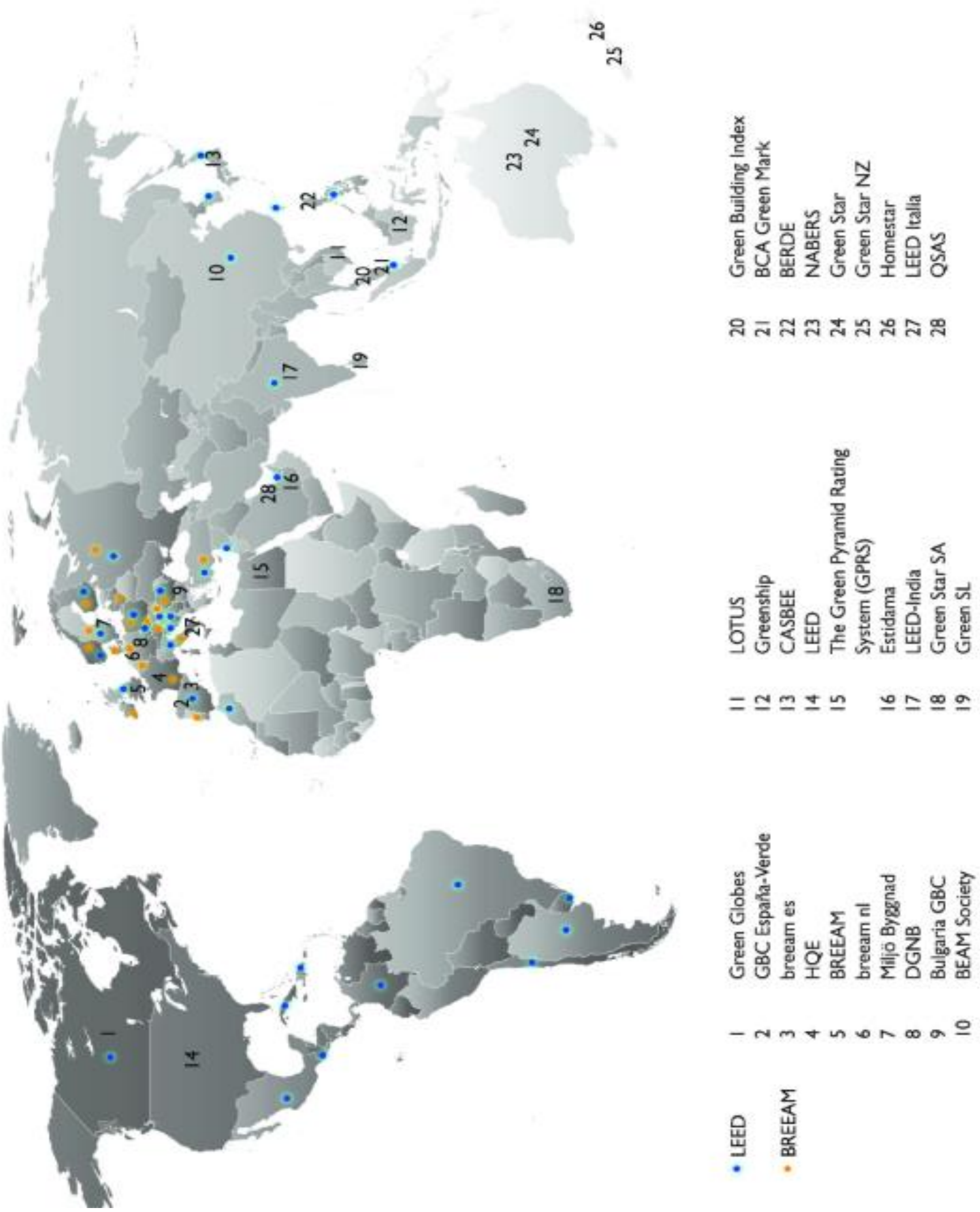


Fig. 2.4 Building assessment tools around the world

From a review of literature on sustainable indicators and criteria emphasizing on building assessment tools, it was observed that the criteria adopted in existing tools cannot directly be suitable and transferrable to other countries. Pertaining to specific conditions like regional variations, climate variations, heritage, culture, and geographical location the indicators and criteria may vary from country to country. It is also clear that, the existing assessment tools in India have some shortcomings and limitations with respect to material performance, transportation and management criteria, thus, given a lesser weight in evaluating the building performance. Further, it was noted that various MCDM techniques are utilized in development of framework for building assessment towards sustainable construction.

2.3 Review of literature on the influence of sustainable material over building performance

With the growing building and infrastructure facilities, the demand for materials and resources lead to disturbance in the environment and destabilization in sustainability (Park et al. 2017). Sustainable construction is a growing concern in the present world, particularly in developing countries like India. Building materials play a vital role in achieving sustainable construction. Unless and until the action for sustainable material consumption and implementation are enforced, energy consumption, waste, and Greenhouse Gas (GHG) emissions continue to grow further (Reddy et al. 2019; Saadah & AbuHijleh, 2010). Different materials may perform differently with respect to a single attribute. To choose an optimal material and achieve the desired results, the requirements should be robust enough to achieve the required performance (Akadiri, 2011; Durdyev & Zavadskas, 2018; Hafezalkotob et al. 2016; Maniya & Bhatt, 2010; Taylan et al. 2015; Xue et al. 2016; Zarghami et al. 2018). For example, in case of concrete, the cost should be reasonable, should be durable and should also obey sustainable design principles. Potential sustainable building materials are based on three sustainability criteria: environmental, social and economic and to design the product for specific needs i.e., Reduce, Reusable Replaceable, Repair and Renovate materials (5R's) are to be considered (Bakhoum & Brown, 2012; Bank et al. 2011; Kisku et al. 2017). The challenge before the construction sector lies in providing building materials with reduced environmental burden, improved social benefit, economic viability and technological feasibility (Mahmoudkelaye et al. 2017; Reddy et al. 2019; Venkatarama Reddy, 2004). The strategies to enhance sustainability is country specific and depends on its size, culture, and economic position. Most of the researchers have studied country-specific parameters for assessing and selecting sustainable construction materials (Šaparauskas & Turskis, 2006). For example, (Al-Hajj & Hamani (2011), Govindan (2015) & Radhi (2010) in UAE, Wang et al. (2018) in Taipei, Ejiga, (2017) in Lagos, Abeysundara (2009) in Srilanka, Akadiri (2012) & Bakhoum & Brown, (2015) in UK.

The developed countries have been emphasizing on Life Cycle Assessment (LCA) and these are location specific which cannot be utilized for others (Curran, 2012; Reap et al. 2008). Also, there is lot of scope for the availability of material inventory data on environmental impacts throughout the lifecycle (raw material, manufacturing, transportation, construction, maintenance, repair, and demolition) to quantify energy and carbon footprint, which makes the material evaluation approach versatile (Cole, 2005). Several LCA based tools specific to a location like ATHENA in North America, ENVEST in the UK and others (Table 2.4), for evaluating the energy and carbon footprint. These tools require the embodied Life Cycle Inventory (LCI) data to find the impacts of the materials (Trusty et al. 2002).

Table 2.4 Widely used Life Cycle Assessment tools in the world

LCA software	Function	LCA software	Function
SimaPro	collect, analyze & monitor sustainability performance of products and services	ECO-it 1.4	materials as production, transport, energy and waste treatment processes
Windchill LCA	give users visibility into LCA data during the innovation and design	ATHENA	Eco-calculator & impact estimator for building materials
EarthSmart	web-based , for Product Design & Marketing	GaBi 4	design sustainable products and processes
PackageSmart	web-based, for packaging	GEMIS	For energy, material, and transport systems
Toovalu	Web based, for Carbon Footprint	GREET Model	for various engine and fuel combinations
Clean CO2	carbon emissions, and management	IDEMAT	for material selections in the design process
SENSE tool	Web based, tailored in the food sector	LLamasoft	Supply chain design, network optimization
Key parameter model	environmental impacts of several similar products	LCAiT 4	environmental assessment of products & processes
ECOLOGIC	comprehensive analyses material manufacturing, energy, and transportation	LCAPIX	software combines LCA and Activity Based Costing in business
BOUSTED	focused on fuel, energy, and materials	openLCA	LC analysis and sustainability assessments
PEMS	data to analyze packaged products	SolidWorks	determine environmental impacts of products
TEMIS	dealing with energy and transportation	TEAM	analyses energy, transport and materials
BEES 4.0	measures environmental performance of building products by using LCA approach	Quantis	Understand environmental impacts of operations, products, services or technology
ECOPACK2000	packaged goods, and impact assessment	SPOLD	used to create, edit, import and export data
Quantis Suite 2.0	focusing on GHG emissions, multi-indicators, and water	TEAM	for evaluate LC environmental and cost profiles of products and technologies
OfE	comprehensive analyses of environmental demand	WISARD	help to decision making and evaluate policy options for disposal of household waste
LIFEWAY	Educational, allows for values assessment	Umberto	to visualize material and energy flow systems
Boustead Model	for lifecycle inventory calculations	CMLCA	Chain Management by LCA
eToolLCD	focus & performance based, genuinely sustainable outcomes	Instant LCA™	Eco-design, measure environmental footprints of their products
EIO-LCA	Economic Input-Output LCA	Earthshift	Building pathways to sustainability

(Source: Curran, 2012)

In the case of developing countries like India, due to inappropriate availability of lifecycle inventory data and unawareness on the process, the significance of material performance over building assessment is not considered (Curran, 2012; G. K C Ding, 2013; F. Pacheco-Torgal, L.F. Cabeza, 2014). It was observed that if the country-specific inventory data is not available completely, most of the researchers developed approaches/frameworks to assess the material performance towards sustainability using various Multi-Criteria Decision Making (MCDM) techniques. The selection of an appropriate material considering many factors and conflicting criteria is considered as MCDM problem. Sustainability material evaluation is a multi-dimensional complex issue and most of the studies have utilized the theories of decision making. Various approaches have been developed to facilitate the selection of optimum material among the several feasible alternatives.

Shanian & Savadogo (2006) proposed a model using ELECTRE an outranking relationship concept which is quite extensive in the analysis.

Rao (2007), developed a model based on a matrix approach & graph theory, which does not consider the judgment consistency of the attributes. (Dehghan-Manshadi et al. (2007), proposed a normalization model based on non-linear transformation with a digitally modified logic method for selection of material. However, this does not have a provision to assess the quantitative attributes. Chatterjee (2009), proposed VIKOR and ELECTRE for selection of materials.

Sarfaraz Khabbaz et al. (2009a), proposed a method using fuzzy logic for selection of material, where it needs many IF-THEN rules which is cumbersome to compute.

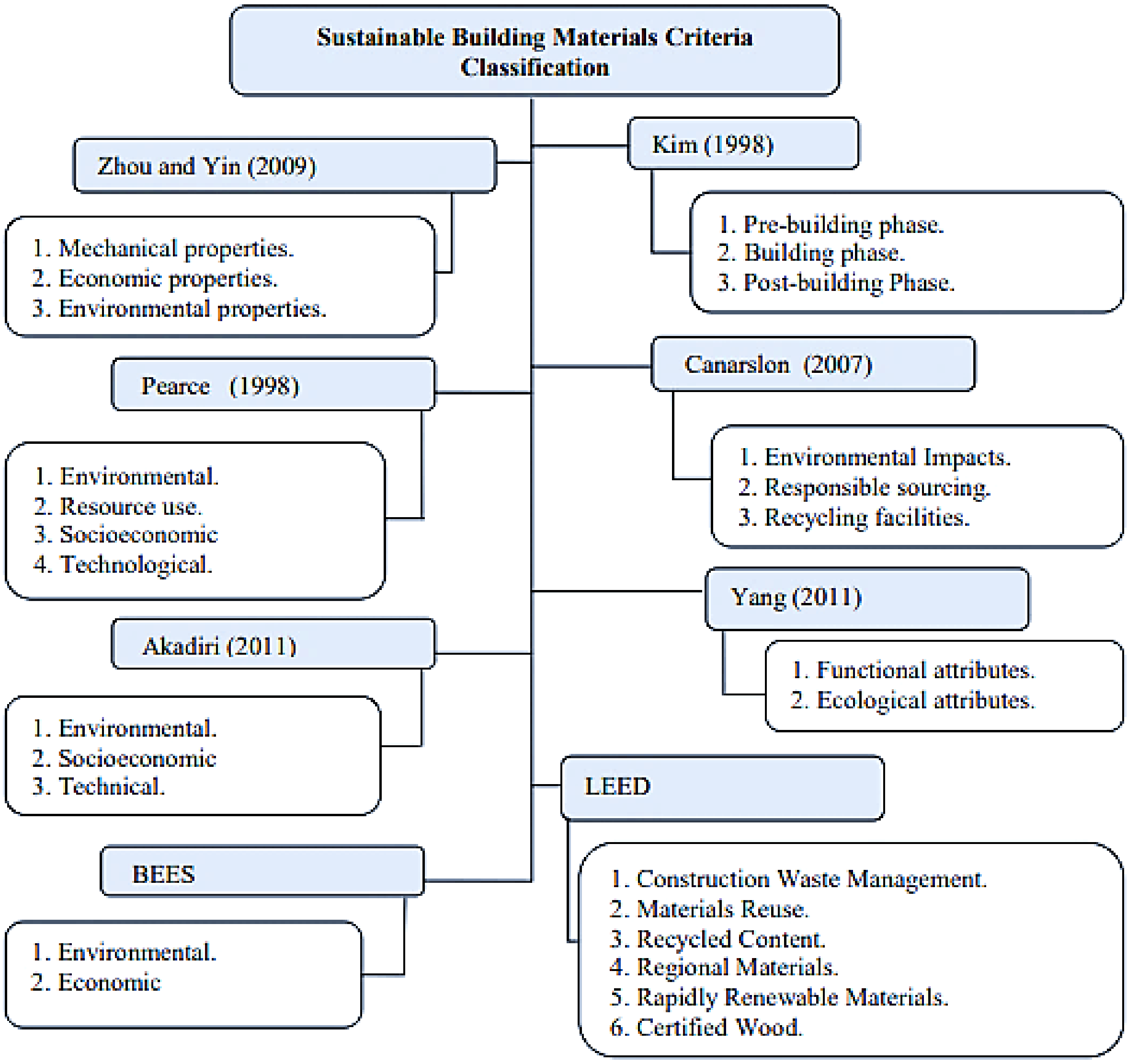
Maniya & Bhatt (2010), developed a Preference Selection Index (PSI) method for choosing the optimum material, where the approach considered only objective weights of attributes and did not account criteria weights. Keeping this in view, Jahan et al. (2011), developed a formula to determine the importance of criteria based on interdependency relationship.

Bakhoum & Brown (2012), focused on the phases of material life cycle, sustainable factors influencing the material evaluation and developed a Material Sustainable Measurement Scale (MSMS). Jahan & Edwards (2013), proposed a model with interval numbers and target-based criteria in the VIKOR method for material selection problems where, it was quite cumbersome to handle and understand. Govindan et al. (2016), proposed a model for the selection of sustainable material using hybrid MCDM approach in UAE.

Liu et al. (2014), suggested an integrated DEMATEL based ANP a hybrid MCDM for criteria evaluation and applied modified VIKOR to improve the consistency of the results, which is very comprehensive to opt. Xue et al. (2016), proposed a model for incomplete weight information using an interval-valued intuitionistic fuzzy set (IVIFSs) and multi-attributive border approximation area comparison (MABAC) for selection of material. The MCDM becomes more complex and challenging when evaluating alternatives involving subjective and objective criteria (Cavallaro, Zavadskas, & Raslanas, 2016; Darko et al. 2019; Hafezalkotob et al. 2016; Kulkarni, Jirage, & Anil, 2017; Medineckiene et al. 2015; Qaemi & Heravi, 2012; Sabaghi et al. 2016; Wang et al. 2015). In the real-time problems, the crisp data is insufficient to deal with vagueness in the decision making (Ribeiro, 1996; Zimmermann, 2001). The human judgments involving ambiguity and vagueness cannot evaluate the actual preferences in crisp values.

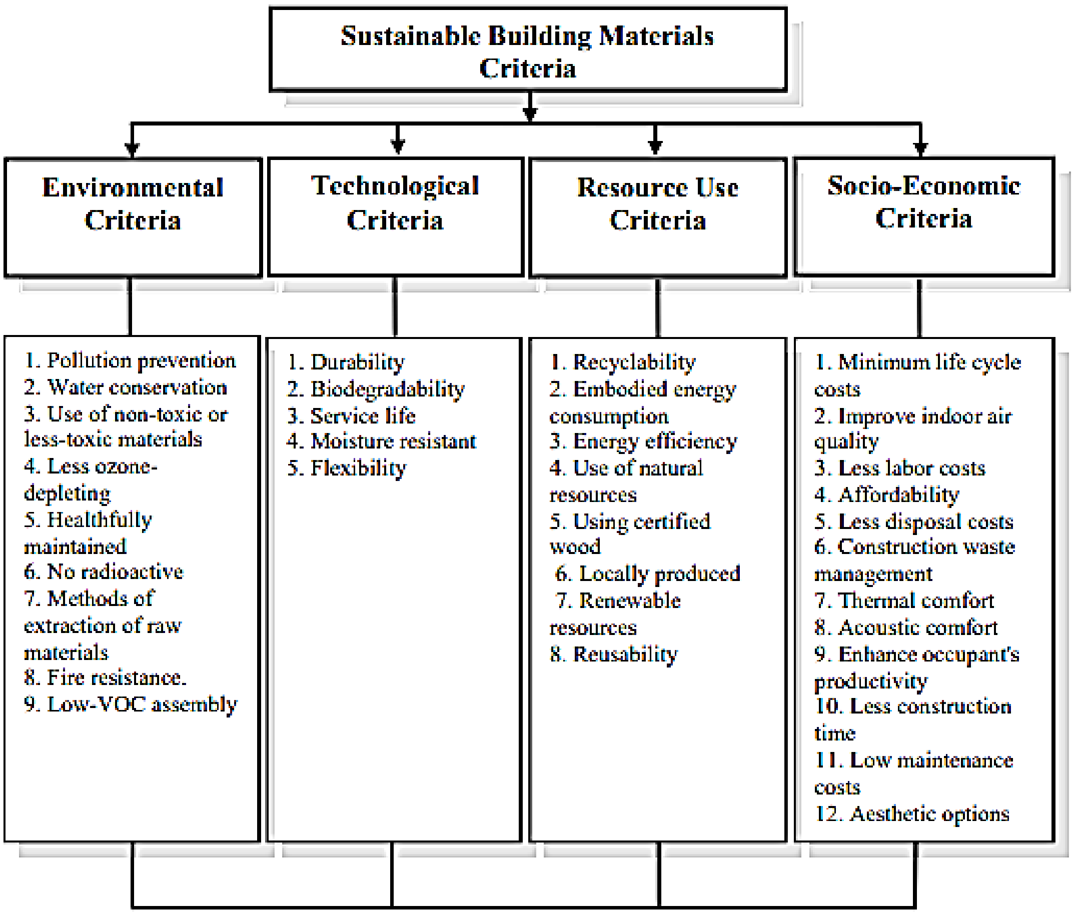
According to Herrera & Herrera-Viedma (2000), the assessment of criteria and factors in linguistic judgments is better than assessment using crisp numerical values. The MCDM technique combined with fuzzy set theory will resolve the vagueness in decision making (Dos Santos, Godoy, & Campos, 2018; Moghtadernejad, Chouinard, & Mirza, 2018). It is noteworthy to observe that techniques like ELECTRE, VIKOR, TOPSIS, Entropy and AHP are widely spread MCDM techniques in the domain of material selection.

According to Kibert (2005), selection of sustainable building material is a difficult task. Various approaches like Hoang et al. (2009), Franzoni (2011) and Shen et al. (2005) noted that durability, recyclability, reusability, energy efficiency and use of local materials should be maximized. Various criteria are considered in building material evaluation by different researchers based on the type of application (Fig. 2.5 & 2.6). Mostly, resource efficiency, waste minimization, life cycle cost, environmental impacts, practicability, flexibility, health and safety, local material usage and pollution are commonly used factors to assess material performance (Akadiri & Olomolaiye, 2012; Bakhoum & Brown, 2015; G. K C Ding, 2013; Ding, 2008; Hafezalkotob et al. 2016; Halliday, 2016; Reddy et al. 2019; Zhang et al. 2017). These factors aid in material selection using various MCDM techniques. The implementation of these sustainable aspects related to material criteria in the construction industry was awarded points by the building assessment tools like BREEAM and LEED (Park et al. 2017).But in the case of developing countries like India, the significance of material performance is disregarded (Gettu et al. 2016; Husain & Prakash, 2019; Prakash & Shukla, 2017; Report, 2016; M. Sharma, 2020; S. Singh et al. 2016).



(**Source:** Baharetha et al. 2012)

Fig. 2.5. Classification of criteria in various studies



(Source: Baharetha et al. 2012)

Fig. 2.6 Various criteria considered in building material assessment

Based on the review of literature on influence of sustainable material over building performance, it was observed that in developing countries like India due to non-availability of appropriate material Life Cycle Inventory (LCI) data, the importance of material criteria is ignored in assessing the building performance. Further, it is noted that various MCDM techniques are utilized in development of framework for selecting a sustainable material among a pool of alternatives. From this broad review, it is also made to understand about the necessity of development of an integrated Graphical User Interface (GUI) keeping in the multifaceted decision making related to multiple indicators, criteria and material performance in developing a framework for building assessment.

2.4 Review of literature on the development of Graphical User Interface (GUI)

The applications of computer graphics is prevalent in various engineering fields. Wilde et al. (2002) suggests, a process based approach integrated with Graphical User interface (GUI) for implementing and monitoring the quality control and performance of any process, methodology or workflow. The representation of graphics in different forms enable users to interpret the data effectively (Kokalj, 2003). For fast and intuitive calculations of logics and generic algorithms, human knowledge is not sufficient to get the output, but GUI constructs the time sensitive service to the user to facilitate quick decisions. A good GUI makes the application more practical, easy, and effective (Hensen, 2004). However, it is still a fuzzy to define a good GUI, conceptually GUI is defined as a "means by which people and computers interact with each other" (Hensen, 2004; Winograd, 1995). Douce (2006), opines that the current generation of assessment tools and systems adopt web-based technologies to expand the public outreach. This represents the overview of the tool and approach adopted in the methodology, which ultimately facilitate the remedial actions to be taken in order to achieve the desired level of progress.

Hai et al. (2011), developed a GUI based software for sustainable assessment version 1.0 using Visual Basic application for calculating the relative weights of indicators using Delphi and Analytical Hierarchy Process (AHP) techniques. The tool integrates techniques and evaluate the ready-made solution in the form of pleasing pictorial representation. This enable the users to easily operate cumbersome calculations with high degree of precision within less time. According to Ghadimi et al (2011), GUI can also enable develop a database for sustainable assessments for products, materials, process and infrastructures. Attia et al. (2013), summarized the challenges and opportunities in integrating simulation based building performance using GUI. It was found that by integrating Net Zero Energy Building tool and Building Performance Optimization tool using genetic algorithm, complex can be solved problems for designers for optimizing the building performance. The developed GUI anticipated the faster computations and improved the communication and visualization results. Further, the GUI facilitated extraction of relevant information from various performance trade-offs. Most of the existing building assessment tools are not embedded with GUI, which makes users to face difficulty in decision making.

Sharipbay et al. (2016) found a number of ways to design a good interface. Two ways of creating a front end page was suggested. The first being content management system and other is with coding based on Hypertext Markup Language (HTML) integrated with Cascading Style Sheets (CSS) for styling purpose. It is important to develop a GUI which serves the purpose and comfortable in using it.

Albani & Ibrahim (2019), developed GUI based simulator for wastewater treatment design process using MATLAB for teaching, learning and assessment purpose. The tool represents the calculation procedure and modelling concepts in one or more windows to perform specific tasks for simulation. This developed model enables users to play an active role while performing simulation. In addition to this, it speeds up the calculation process accurately and displays the results pictographically for quick and better understanding. GUI is hence a combination of various technologies to provide platform for users to interact effectively.

Barıs Simsek et al. (2019), developed the graphical interface to improve and monitor concrete production established using Multi Attribute Decision Making model based on Taguchi optimization and TOPSIS method. This GUI help concrete producers to enhance the quality control and optimize the concrete performance and further decrease the production variance and rescue from laboratory intuitive errors and complex mathematical calculations.

Based on the review of literature on development of GUI, it is clear that the application becomes more practical, easy, and effective with the development of GUI for sustainable building assessment framework. Further, this development of model enable users to play an active role while assessment of the building infrastructure. In the current generation, use of smart phone has become very essential. So, the present study would employ web-based technologies to expand the public outreach by generating QR code for the created GUI web link.

2.5 Summary

In this chapter, a review of literature available on the sustainable construction, sustainable indicators and criteria with an extension to existing building assessment tools, material performance over building assessment were discussed. The need for development of GUI was also discussed. The indicators and criteria considered by various researchers and existing tools in assessing the building performance was discussed. The shortcomings of existing tools to suit the India context is brought out. Also, the importance of material inventory data in evaluating building performance in developing countries like India is highlighted. Based on this broad literature review, the scope and objectives of the present study are defined and detailed in the next chapter.

CHAPTER - 3

SCOPE AND OBJECTIVES OF THE STUDY

3.0 General

A detailed review was reported on sustainable development with a focus on building assessment tool. The literature review was carried out to check if there is any building assessment tool which is suitable to region, climate conditions, culture, heritage and topographical conditions of developing countries like India, based on Social, Environmental, Economic and Technological (SEET) aspects. The study also emphasized on the use of existing tools for their suitability, similarities and differences and further checked the possibility of transferring and adapting to the prevailing conditions without the need for life cycle inventory data. The following are the observations reported from the literature review.

1) The factors influencing sustainable construction that affects the building performance towards sustainability were highlighted.
2) It was observed that the performance of the buildings was discussed considering the environmental dimension only. While some of the researchers considered both environmental and economic dimensions to observe the impacts, burdens and cost implications.
3) There are very few studies on the building assessment based on Triple Bottom Line (TBL) approach i.e., Social, Environmental and Economic dimension. However, these lack the interrelationship among the dimensions. Also, the assessment tools developed for one nation or region might not be applicable to others.
4) It has been observed that, ‘Technological’ advances has always been the cornerstone in mitigating the unavoidable side-effects of development and in surpassing the limits/constraints dictated by the other indicators of sustainability vis-à-vis Social, Economic & Environmental.
5) From the literature review, it is felt imperative to incorporate the technological dimension by rejuvenating ideas of reuse, recycle, reduce, renew, and regenerate into implementable solutions to the existing TBL to achieve a complete sustainable construction SEET indicators.

6) Most of the assessment tools utilized the Analytical Hierarchy Process (AHP), a Multi-Criterion Decision Making (MCDM) method to assess the relative weight but could not capture the vagueness and uncertainty in decision making.
7) It was observed that the concept of fuzzy logic is utilized in order to capture the ambiguity and vagueness of the respondents. It can also be inferred that the Delphi Technique is observed to be preferable to reach a consensus on the identified criteria based on previous studies.
8) It was felt that attention needs to be given while deciding the applicable criteria and sub-criteria compatible to Indian context, which exhibits a wide range of climates, cultures, and topographic features. This it would benefit in implementing a domestic assessment method for measuring building performance. This is a potential area of investigation.
9) It was observed from the studies that due to the nonavailability of appropriate life cycle inventory data for building materials in developing countries like India, the existing assessment tools (GRIHA, LEED, and IGBC) has disregarded the material component in evaluating the sustainable building performance. Hence, there is a need to study the behavior of material performance towards sustainability.
10) It was also felt that there is a necessity to develop a Graphical User Interface (GUI) system, a self-assessment tool to assess the sustainable building performance of the habitat.

3.1 Scope of the study

The scope of the present study includes the following

1) Based on the available existing assessment tools, guidelines and policies, the criteria and attributes are identified considering regional context, climate conditions, culture, heritage and topographical conditions that prevail in India.
2) Assign and standardize the relative weights for sustainable indicators, criteria and establish inter-relationship between them.
3) Distribute credit points to sustainable attributes corresponding to each criterion so as to quantify the building performance and thus generate a sustainable building performance score.
4) Assess the material performance towards sustainability by generating a material index considering material life-cycle phases.

5) Develop a Graphical User Interface (GUI) web portal using HTML, JavaScript and other technologies to assess the building performance score and thus rate the building.

3.2 Objectives of the study

1) To identify, compare and evaluate relative weights of sustainable criteria and indicators (SEET) and establish Inter-relationship between them based on existing tools (LEED, BREEAM, GRIHA, and IGBC), guidelines and policies.

2) To obtain the relevant quantifiable attributes and pre-requisites for each criterion and assign weights to them for assessing the building performance.

3) To evaluate the building material index by integrating sustainable SEET indicators, factors influencing material sustainable performance and material life-cycle phases, without the need for inventory data.

4) To develop a sustainable building performance scoring system based on relative weights of criteria and global weights of sustainable attributes; and thus develop Sustainable Building Assessment Tool (SBAT), an automated Graphical-User-Interface (GUI) tool embedded with a QR code.

3.3 Research Methodology

To achieve the above-mentioned objectives of the study, a detailed program is designed and carried out in Four Phases.

Phase - I

The comparison of existing building rating systems like LEED, BREEAM, GRIHA and IGBC and various other sources was carried out to identify the potential criteria and attributes. They are then screened and diagnosed to suit the Indian context using the Delphi Technique (DT). The relative weights of SEET indicators and criteria are evaluated utilizing the concept of Fuzzy Analytical Hierarchy Process (FAHP). Based on the relative weights of the indicators and criteria obtained, the inter-relationship among them is established.

Phase – II

Based on the existing assessment tools, guidelines, policies and field practices, the pre-requisites are recognized. This is keeping in view the regional context, culture, heritage, topographic features, and level of public awareness in India, to assess the attribute performance. Each attribute is assigned with a quantifiable relative weight using FAHP and a set of performance benchmarks are assigned that are largely quantifiable and assessable.

Phase – III

To assess the performance of building material towards sustainability, the sustainable factors that influence the material selection are identified and are categorized with respect to quadruple-bottom line (SEET) approach. This phase integrates three ideas: Sustainable factors, SEET indicators and Material life cycle phases in developing Sustainable Material Performance Indices (SMPI) for a selection of material alternative.

Phase – IV

Based on the assigned relative weights to criteria and global weights to attributes, Sustainable Building Performance Score (SBPS) is evaluated. A GUI web page embedded with QR code is developed for the easiness and will act as a self-assessment tool for the users of the building.

A schematic diagram showing the detailed research methodology for each phase of work involving methods used along with the output of the research investigation is given in Fig. 3.1.

Fig 3.2 shows the sustainable criteria and corresponding attributes for assessing the building sustainable performance embedded with a QR code.

Similarly, Fig 3.3 shows the step by step methodological approach in each phase of research work to develop the Sustainable Building Assessment Tool (SBAT)

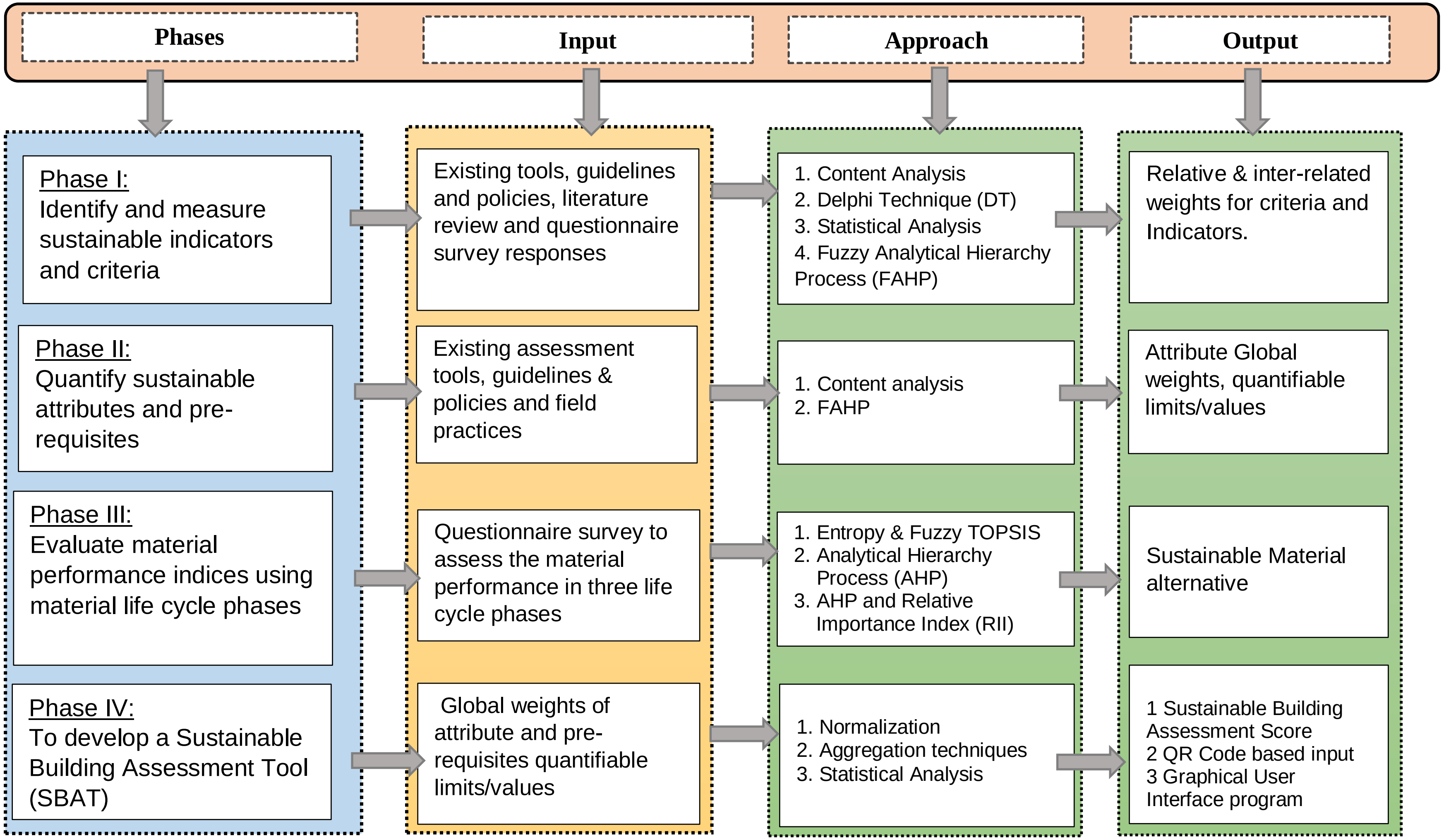


Fig 3.1 Research Methodology

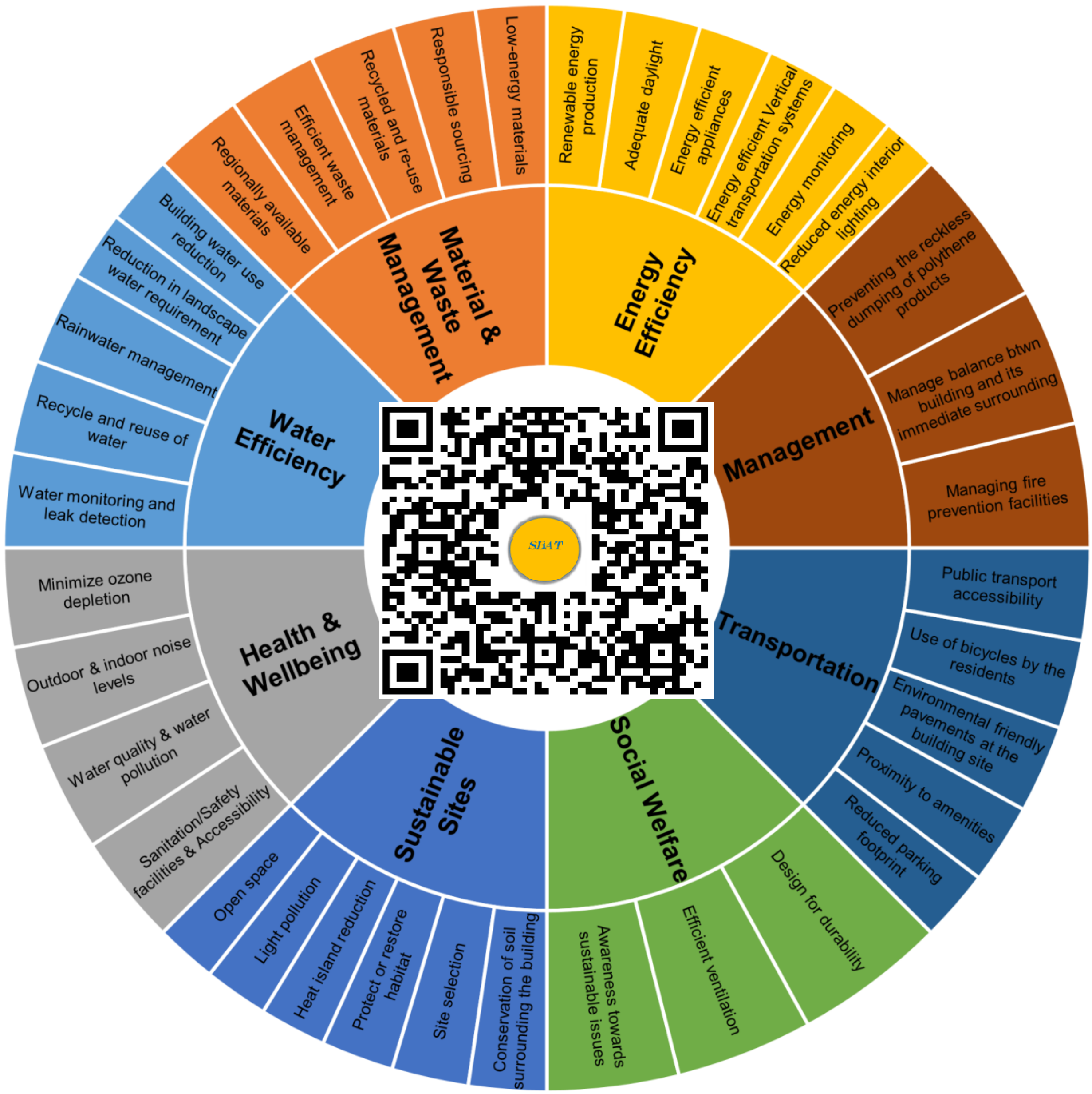


Fig. 3.2 Sustainable criteria and Attributes Embedded with QR code

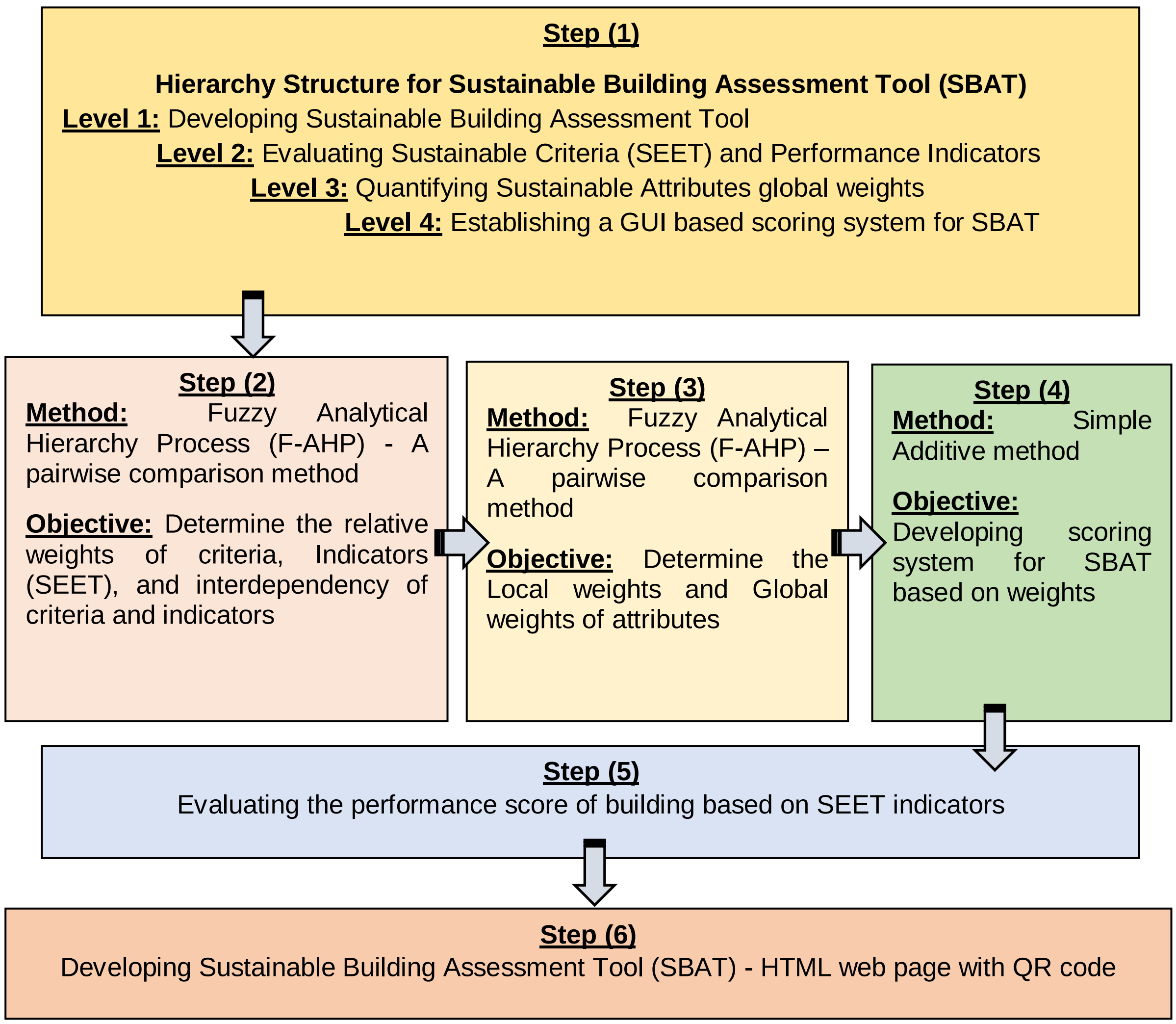


Fig. 3.3 Framework to develop Sustainable Building Assessment Tool (SBAT)

CHAPTER - 4

BENCHMARKING SUSTAINABLE ASSESSMENT INDICATORS AND CRITERIA USING FUZZY ANALYTICAL HIERARCHY PROCESS (FAHP)

Phase I

Objective: To identify, compare and evaluate relative weights of criteria and indicators (SEET) and establish inter-relationship between them.

4.0 Introduction

The global problem of environmental degradation has forced society to rethink infrastructure development to evolve the concept of sustainable development in the construction industry. Sustainable development, however, involves the design of integrated approach that can address building sustainability, while ensuring social and economic prosperity at the national or even global level implying a macroeconomic scope. Indeed, the new sustainable friendly technologies, methods and materials in the civil engineering field are fundamental to attain sustainable development.

The growing urbanization demand in developing countries like India is accompanied by a rapid increase in energy consumption and carbon emissions. The building sector accounts for 33% of total Indian energy consumption (Economic Policy Forum, 2014). So, unless specific policies are implemented, this energy demand will further increase to as high as five times by the year 2100 (Vyas & Jha, 2016). This acute problem of urban development in India will face monumental challenges (Smith, 2015). According to The Energy Resources Institute (TERI), India needs to take drastic measures to improve energy efficiency (Singh et al. 2016). To tackle the enormous changes in urban transformation, it is important to have a paradigm shift in urban development to sustainable development (Reddy et al. 2018). In the previous chapters, the significance of criteria, indicators and building rating system was discussed and pertinent objectives were laid in Chapter-3 (Scope and Objective). This chapter focusses on identifying, comparing and evaluating relative weights of criteria and indicators, to establish the interrelationship between them for assessing sustainability. The chapter is dealt in four stages: Comparison, Identification, Evaluating relative weights and establishing interrelation weight.

4.1 Indian Sustainable Built Environment

Building construction uses the land, energy, water & natural resources, and produces waste and releases hazardous gases causing ecological imbalance. By incorporating sustainable principles in the construction sector, buildings can develop the capacity to curtail Green House Gas (GHG) emissions and reduce carbon footprint (Jain et al. 2013). Buildings could create negative impacts during pre-construction, construction phase and while operation and maintenance (post-construction) phase. A green/sustainable building is defined as "a building that can coexist with nature, maximize resource conservation (energy, land, water, and materials), reduce pollution in its whole life cycle and deploy the efficient use of space" (IGBC Green New Rating System version 3.0, 2015). The stakeholders of sustainable buildings shall realize that these not only have sustainable performance, but also, has a payoff fiscally (Jain et al. 2013). Compared to developed countries, developing countries have got a new trend of accepting green building guidelines (Korkmaz et al. 2008). According to the United States Green Building Council (USGBC, 2014), every country is in the process of developing its own rating system or guidelines to achieve an overall sustainable built environment. For example, prominent assessment tools like the Leadership in Energy and Environmental Design (LEED) scheme in the US, the Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) in Japan. The Building Research Establishment's Environment Assessment Method (BREEAM) in Australia also use the country-specific format of Norway, Sweden, Spain, and the Netherlands. Based on the LEED revision, India introduced the Indian Green Building Council (IGBC) assessment method in the year 2000. Subsequently, The Energy and Resources Institute (TERI) has developed an Indian national green building rating system, Green Rating for Integrated Habitat Assessment (GRIHA) in 2007 (Vij et al. 2010).

In India, there are efforts to look into every possible way to boost up the infrastructure development, for instance, in the 12th Five Year Plan (FYP) Government of India has increased investments in infrastructure sector to one trillion US $ (Tathagat &

Dod, 2015) with specific focus on urban transformation like development of Smart City Mission, Atal Mission for Rejuvenation and Urban Transformation (AMRUT), and Heritage Cities Development and Augmentation Yojana (HRIDAY), which can mainly boost the sector (Singh et al., 2016). Even the Bureau of Indian Standards (BIS), has prepared the National Building Code of India in the year 2005, to regulate the building construction activities across the country and initiated an approach to achieve sustainability through National Building Code (NBC) 2005 Part 11 (CPWD, 2014). The FYP aims to accelerate the approval and implement codes related to green building through Jawaharlal Nehru National Urban Renewal Mission (JNNURM) and by linking financial decentralization to local urban authorities for implementing green building codes. The National Action Plan on Climate Change (NAPCC) and the National Mission on Sustainable Habitat addresses energy efficiency in the buildings. The Bureau of Indian Standards (BIS) and the Building Materials and Technology Promotion Council (BMTPC), are involved in promoting eco and affordable housing, sustainable building materials, and their production and development of regulatory standards. The standards and labeling are practiced by Bureau of Energy Efficiency (BEE) to surge the awareness and reduce energy consumption (Bureau of Indian Standards, 2012).

The assessment methods created for one nation or region might not be applicable to others, because, a number of factors may prevent the transfer of currently available environment assessment tools to other nations. Some of these factors include site conditions, climate, geography, resource consumption and level of public awareness. Sustainable development is an interdisciplinary approach to meet human needs optimally using limited natural resources (Raphael, Madras, & Roussel, 2017) and facilitates the transfer of these resources to future generations. This emphasizes sustainable development and economic growth without compromising environmental protection, social needs, and technological features (Hongxun Liu & Lin, 2016). Inadequate understanding of the interdependency among dimensions and cumulative impacts of them further compound the difficulty to achieve sustainability (Ugwu & Haupt, 2007). There are very scarce studies to evaluate the performance of buildings in India, like Green Rating Integrated Habitat Assessment (GRIHA) and Leadership in Energy and Environment Design (LEED) operated by Indian Green Building Council (IGBC). However, this is a macro-level strategy formulation, but noticeably weak in micro-level strategy. India exhibits a range of different climates, cultures, and topographic features and would benefit from implementing a domestic assessment method of measuring building performance. However, LEED attempted to make their assessment tools compatible with the conditions of different regions in the World. It is however revealed that they were not able to fully incorporate the social, economic and cultural elements in the sustainability assessment criteria.

Most of the certified green buildings in India belong to the government or private agencies. The reason why residential buildings are not perused is due to the limitations of the existing frameworks. There are no systematic means to identify, whether, the building is practically meeting sustainability intended standards. The growth of green/sustainable building in Indian scenario is shown in Fig 4.1. From the case study conducted by Gesellschaft für Internationale Zusammenarbeit (GIZ) and the Overseas Development Institute (ODI), under the umbrella of the Economic Policy Forum (EPF) supported by the German Ministry for Economic Cooperation and Development (BMZ) on “Promoting sustainable and inclusive growth in emerging economics: Green Buildings”, it was acknowledged that developing countries need further action and development in three broad areas: 1) Policy and regulation: strengthening the regulatory authorities and reinforcing the existing laws towards sustainability (Danjaji and Ariffin, 2017). 2) Capacity and skills: Lack of technical skill for the construction process, and 3) Awareness and understanding of benefits: Lack of awareness towards sustainability/green practices and their benefits (Economic Policy Forum, 2014).

Considering the need for developing a domestic building assessment tool, GRIHA, the national green building rating system, was developed by TERI (The Energy and Resources Institute) in 2007 after a thorough study and understanding of the current internationally accepted green building rating systems and the prevailing building practices in India. But, one could find some of the criteria like Transportation and Management were not considered in GRIHA for environmental assessment. Hence, it is felt from the literature study, that there is an urgent need to identify and develop an interrelationship between the criteria and indicators to assess the building sustainability considering local context, climate conditions, culture, topography, and ethical aspects that prevail in developing countries like India.

Fig. 4.1 Growth of Sustainable/Green Building scenario in India

4.2 Research focus

The significant criteria that can assess the sustainable performance of a building identified based on the existing assessment tools, guidelines, policies and related publications considering local context, climate conditions, culture, topography, and ethical aspects that prevail in the developing countries like India were considered.

Based on the comparison of tools like BREEAM, LEED, IGBC, and GRIHA, the criteria, and sub-criteria are assessed and checked for the possibility of transferring and adopting in the Indian context. While diagnosing the similarities and differences in various existing tools, the study emphasized on the suitability of potential and possible criteria to be considered in developing countries like India and its state of affairs. Further, the diagnosed criteria are refined and screened out using Delphi Technique (DT) (Ramos & Caeiro, 2010) to reach a consensus on the identified criteria and understand the depth of each of the criteria and their related attributes for quantification. The DT was performed with the data obtained from six experts having a minimum of 20 years of experience in the domain area of sustainable construction, each belonging to categories such as Academicians, Engineers, Designers, Architects, Consultants, and Others to finalize the criteria and their related attributes. The criteria whose Relative Importance Index (RII) value is more than or equal to 0.7 has been screened out for selecting the most significant attributes. A total of eight criteria and 37 attributes were established to evaluate and assess the building performance towards sustainability.

To evaluate the relative weights of criteria and indicators, the present study collected the data from a structured questionnaire survey responses (96 no's) from all the stakeholders of the construction industry, each belonging to categories such as Academicians, Engineers, Designers, Architects, Consultants, Contractors and Others. Inappropriate and incomplete response data is screened out and finally 58 responses are found to be applicable. The questionnaire is formed in such a way that the relative importance of criteria with respect to each indicator (SEET) is obtained on a 7 point Likert scale. The consistency of the data is checked using Cronbach's Alpha coefficient before performing statistical methods (Vaske, Beaman, & Sponarski, 2017). Further, the study utilized the Analytical Hierarchy Process (AHP), a Multi-Criteria Decision Method (MCDM) in assigning the relative weights to criteria and indicators. In order to capture the ambiguity and vagueness of the respondents to the questionnaire, the concept of fuzzy logic is integrated with AHP and termed as Fuzzy AHP (FAHP), a Hybrid Multi-Criteria Decision Method (HMCDM) for assigning the relative weights. To perform FAHP, a number of pairwise comparisons for the Four sustainable indicators and Eight sustainable criteria for each respondent (Total 58) were performed. A total of {58 x 8 x 4 x 4} matrices were developed to assign relative weight to sustainable indicators (SEET). Similarly, a total of {58 x 4 x 8 x 8} matrices were developed to assign the relative weight to sustainable criteria.

4.3 Quadruple Bottom Line (QBL) Approach

A building construction project is considered as sustainable, only when all the dimensions of sustainability are taken into account. Most of the issues of sustainability are interrelated in existing methods, and the focus is mainly given to environmental aspects. However, presently, there is no specific assessment tool that encompasses the SEET aspects. This clearly specifies disregard to the economic, social and technological aspects of sustainability, which could further lead to ecological imbalance and thereby, miss the real goal of sustainable development. India exhibits a range of different climates, cultures, and topographic features and would thereby benefit from incorporating these features in sustainable building assessment method (Alyami & Rezgui, 2012). Though LEED has attempted to make their assessment tools compatible with conditions of different regions in the world, it was not able to fully incorporate the social, economic and cultural elements in the sustainability assessment criteria (Banani et al., 2016). The existing building assessment tools are hence, limited to unidimensional sustainability.

Sustainable building assessment was based on a triple bottom line approach (Bhatt et al. 2010) i.e., Environment, Social, and Economic Dimensions. It was also observed that the building assessment criteria were developed to originally suit a specific region. In line with Horvat & Fazio (2005) and Sev (2011), LEED and BREEAM hence overlooked some of the sustainable criteria and category. According to Alyami et al (2015), in Saudi Arabia socio-cultural, economic and general management aspects are included in the existing assessment tool. Similarly, Ding (2007), advised that the building assessment method has a variety of criteria, related to sustainable development the Environment, Social and Economic are said to be Triple Bottom Line (TBL). An in-depth study of the literature indicated that the Technological component's significance can be enhanced by incorporating recent technological advances in the sustainability of the construction sector. Technological advances have always been the cornerstone in mitigating the unavoidable side-effects of development and in surpassing the limits/constraints dictated by the other indicators of sustainability vis-à-vis Social, Economic & Environmental. For instance, a shift from working stress method to limit state method in the design philosophy led to thinner and more economical sections without compromising the safety and durability, an introduction of steel columns and steel beams in lieu of stone walls as structural materials made the towering skyscrapers possible. The existing triple bottom line indicators though indirectly take various technological/engineering processes into consideration, more emphasis shall be laid on Technological aspects.

The technological dimension can be incorporated by rejuvenating ideas of reuse, recycle, reduce, renew, and regenerate into implementable solutions to the existing TBL to achieve sustainable construction. In simple words, to transform a theoretical concept into practical implementation, various techniques and methodologies are required for benchmarking the threshold values and targets. Secondly, it needs policies and guidelines for proper governance in particular. Finally, it is necessary to understand that the co-benefits of supporting technique and technology lead to sustainable harmony in the construction industry. The significance of this study lies in determining the interrelationship between the SEET indicators and criteria using Fuzzy Analytical Hierarchy Process (FAHP), a Hybrid Multi-Criteria Decision Making (MCDM) method.

4.4 Fuzzy numbers and Linguistic terms

Lofti Zadeh (1965), introduced Fuzzy set theory in order to make decisions for problems dealing with vagueness, subjectivity, and imprecision. Fuzzy comes into play when the judgment is not well defined and does not have proper boundary/limit. In fuzzy set theory, each element is assigned with a membership value to determine the degree to which the element belongs to a fuzzy set ranging from 0 to 1. The concept of quantitative evaluation using linguistic terms is subjective in nature and involves vagueness. For this, the fuzzy set theory captures and resolves the ambiguity involved in the judgment (A. P. C. Chan, Chan, & Yeung, 2009).

The fuzzy set denoted by 'A' is defined by $\mu_A(x)$: X→[0,1] on the universe of discourse, where, each element of 'x' is well-defined to a membership value $\mu_A(x)$ between 0 and 1(When $\mu_A(x)$ =0 the element x does not belong to set A and when $\mu_A(x)$ =1, the element 'x', absolutely belongs to set A). Since there does not exist absolute membership values, generally, subjectivity is assessed based on the context. In the present study, the triangular fuzzy number is preferred to handle the subjectivity of the decision maker.

4.4.1 Membership Function

A membership function for a fuzzy set 'A' on the universe of discourse 'X' is defined as μ_A: X → [0, 1], where each element of X is mapped to a value between 0 and 1. This membership value or degree of membership quantifies the grade of membership of the element in X to the fuzzy set A. In Fig. 4.2, the x-axis represents the universe of discourse, whereas the y-axis represents the degree of membership in the [0, 1] interval. Defining fuzzy concepts, using more complex functions does not add more precision. Hence, in the study, simple functions are used to build membership functions.

4.4.2 Triangular Fuzzy Function

Triangular Fuzzy Numbers (TFN) are expressed in linguistic terms and are defined by a lower limit 'a', mean value 'b' and an upper limit 'c'. It is usually employed to capture the vagueness of human judgment related to decision making. Instead of crisp numbers, the TFN's are expressed with boundaries to reflect the fuzziness in conducting pairwise comparison shown in Table 4.1. Consider a TFN defined by $\tilde{A}$= (a, b, c), where $\mu_A(x)$ is the degree of belonging or membership value of the element in the universe of discourse (Fig. 4.2).

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a}, & \\ \frac{c-x}{c-b}, & \\ 0 & \end{cases} \begin{bmatrix} a \le x \le b \\ b \le x \le c \\ otherwise \end{bmatrix} \quad \text{(Eq. 4.1)}$$

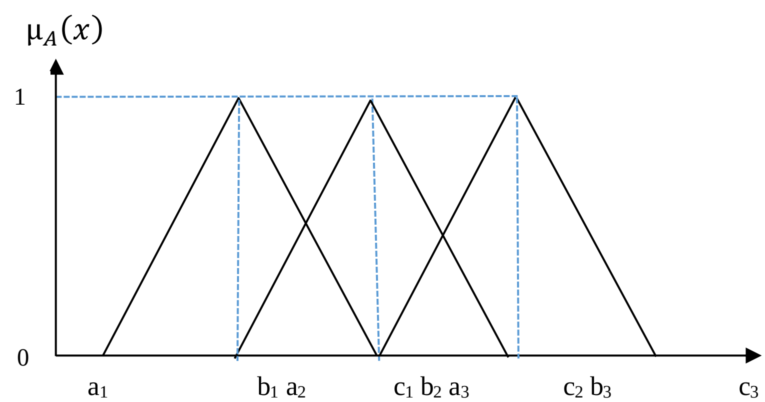


Fig 4.2 Triangular fuzzy number

Consider two fuzzy numbers $\widetilde{A_1}$ and $\widetilde{A_2}$, where $\widetilde{A_1}$ = (a_1, b_1, c_1) and $\widetilde{A_2}$ = (a_2, b_2, c_2) whose operations of addition, multiplication, division and reciprocal are defined by Equations 4.2 to 4.5

$\widetilde{A_1} \oplus \widetilde{A_2}$= ($a_1+a_2$, b_1+b_2, c_1+c_2) (Eq. 4.2)

$\widetilde{A_1} \otimes \widetilde{A_2}$= ($a_1 \otimes a_2$, $b_1 \otimes b_2$, $c_1 \otimes c_2$) for $a_1>0$, $b_1>0$, $c_1>0$ (*i* =1,2) (Eq.4.3)

$\widetilde{A_1} / \widetilde{A_2}$= ($a_1/c_2$, b_1/b_2, c_1/a_2) for $a_1>0$, $b_1>0$, $c_1>0$ (*i* =1,2) (Eq. 4.4)

$\tilde{A}_1^{-1}$= (1/c_1, 1/b_1, 1/a_1) for a_1>0, b_1>0, c_1>0 (Eq. 4.5)

Table 4.1 Linguistic Terms and corresponding Triangular Fuzzy Numbers

Saaty scale	Definition (Level of Importance)	Fuzzy Triangular Scale
1	Equal	(1, 1, 1)
3	Weak	(2, 3, 4)
5	Fair	(4, 5, 6)
7	Strong	(6, 7, 8)
9	Absolute	(9, 9, 9)
2 **4** **6** **8**	Intermediate values	(1, 2, 3) (3, 4, 5) (5, 6, 7) (7, 8, 9)

4.5 Study Approach

The assessment methods created for one nation or region are not applicable to others because a number of factors prevent the transfer of currently available assessment tools to other nations (Banani et al. 2016; Mao et al. 2009; Alyami & Rezgui 2012). Some of these factors include site conditions, climate, geography, resource consumption, regional context level of public awareness, etc. The identification of criteria related to sustainable construction from various sources including existing building rating systems was carried out to address Agenda 21 (Laul, 2001) and UN initiatives towards sustainability. The three pillars (Environmental, Social and Economic) were studied along with technological aspects, which has been lagging behind for achieving sustainable construction in terms of policies, guidelines, standards, technical capability, and skill.

a) **Indicators:** The multi-dimensional pillars for achieving sustainable construction are identified based on the needs, benefits, impacts, and goals. The present study considered the quadra bottom line approach (i.e., SEET) as indicators (Fig. 4.3).

The "*environmental"* indicator relates to effects on ecology and atmosphere, emissions, environmental protection measures, conservation of energy and water. The "*Social"* aspects involve the effects of the local context, employment, serviceability, public safety, sanitation, community development, human well-being, and cultural heritage. The "*Economic"* aspect refers to market supply and demand, financial investment, payback returns, valuation, and life cycle cost. The "*Technological"* aspects relate to innovative practices and the use of sustainable materials, specific design strategies for sustainable construction practices and assessment tools.

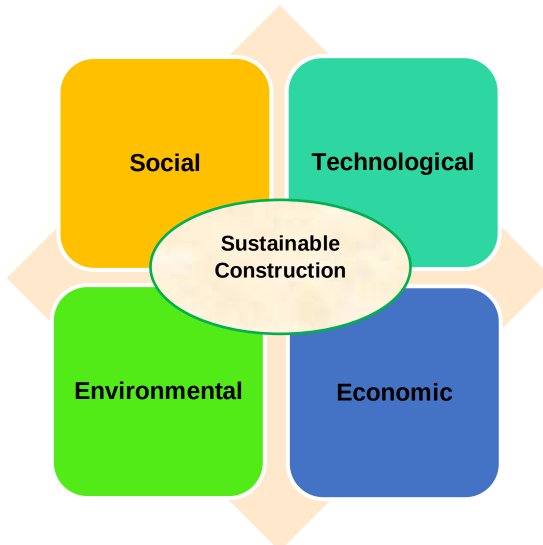


Fig. 4.3 The Quadra Bottom Line for achieving Sustainable Construction

b) **Criteria:** These are the overall performance measurement indents for assessing, promoting and implementing sustainability in buildings.

c) **Attributes:** An attribute deals with the measure of performance of building sustainability. A group of attributes categorized under each criterion will address the specific importance.

The study approach in this chapter/phase is hence designed to

- Compare existing tools, policies and guidelines and consolidate the indicators and criteria
- Form an expert panel for the study
- Conduct Delphi technique to reach a consensus on the identification of criteria
- Establish and refine the significant criteria and indicators;
- Evaluate relative weights to observe the performance of criteria w.r.t. indicators.
- Establish interrelationship between criteria and indicators

The methodology to assess the relative weights for criteria and attributes and establish the interrelationship between them is shown in Fig. 4.4 and the theoretical outline of the study is shown in Fig. 4.5.

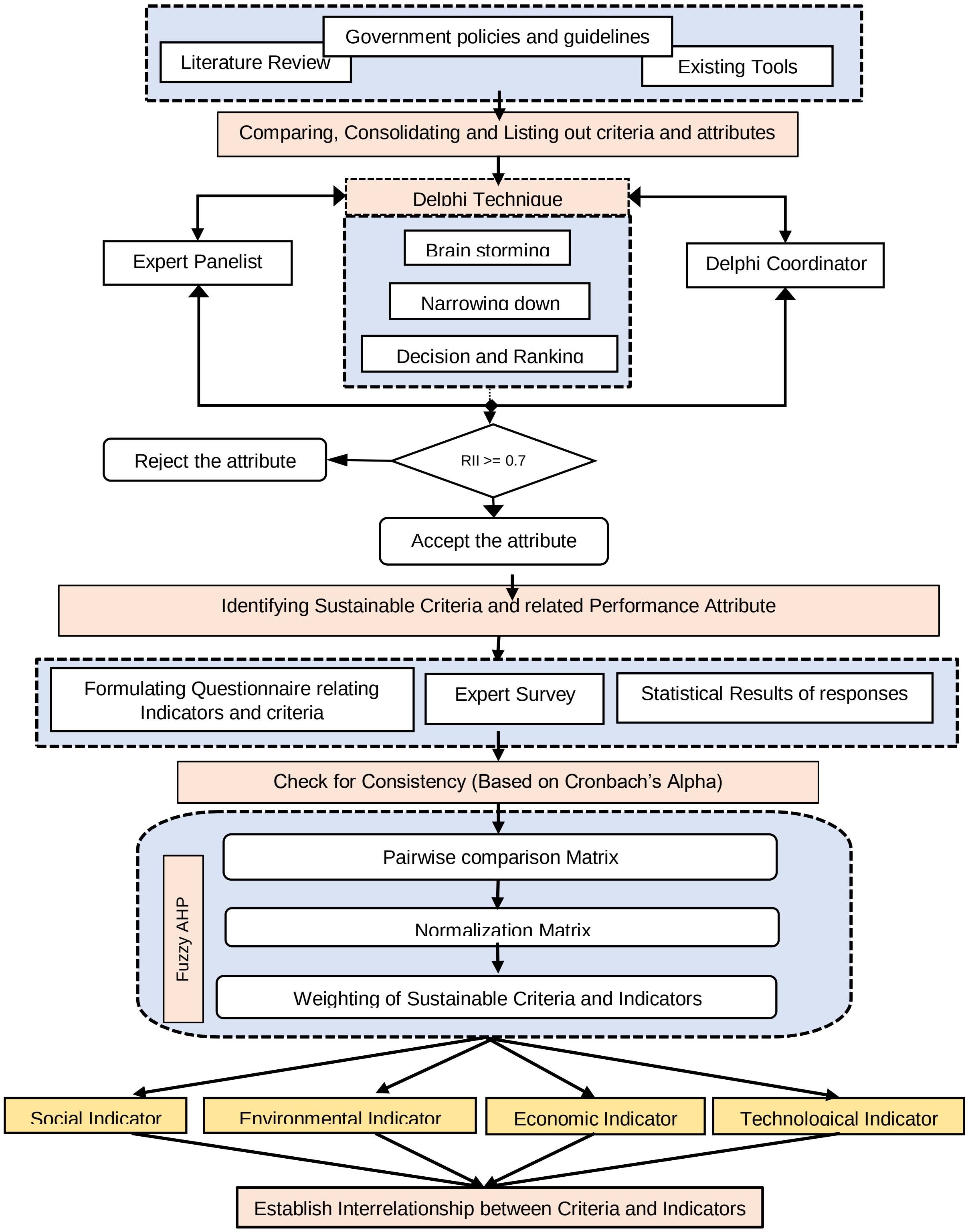


Fig. 4.4 Methodology to assign relative weights and establish interrelationship for criteria and indicator

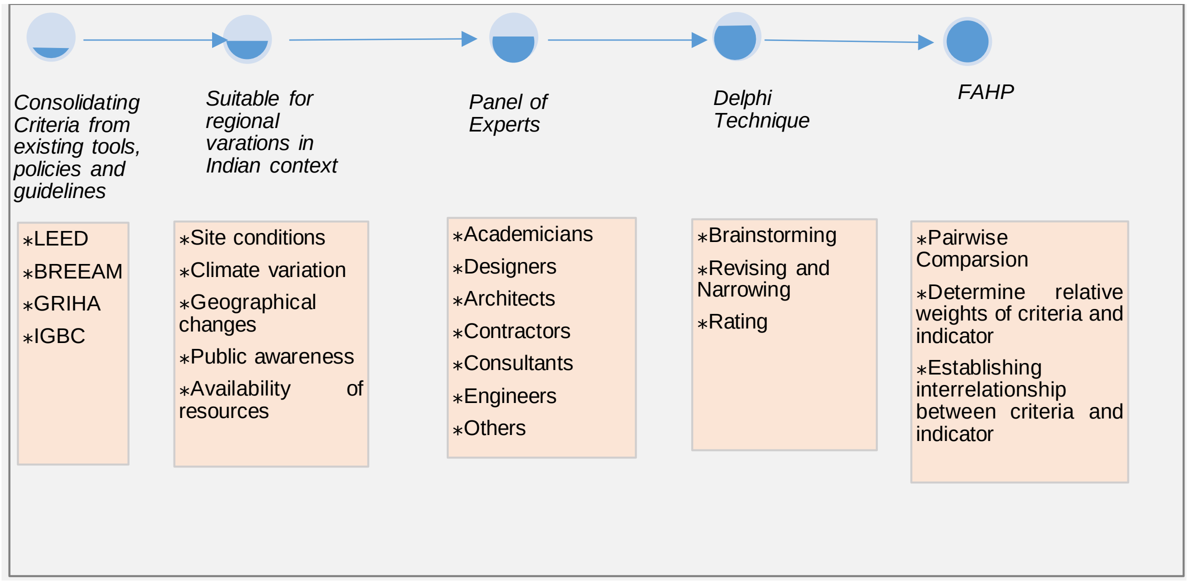


Fig. 4.5 Theoretical outline of the study

4.6 Comparison of Existing Building Assessment Tools

According to Cole (2005), the development of an assessment tool from a comparative analysis of existing ones is a dynamic start for new assessing methods. There are several building assessment tools available in the world. Some of them are the most prominently used tools with criteria and sub-criteria. Based on the credibility and recognition of the rating system in the market, four assessment tools were selected, compared and analyzed for similarities and dissimilarities. Though these rating systems seem to have some criteria in common (names) they differ in their meaning and understanding. This is mainly due to varied climate, culture, region, awareness, practices and assessment method. In addition to this, the rating systems are not unique in nature, dimension and comply with the requirements. The assessment tools Leadership in Energy and Environment Design (LEED) and Building Research Establishment Environment Assessment Method (BREEAM) being the most prominent and established assessment tools, recognized globally in the domain of sustainable construction are considered in this research work. The other two methods originated in India say GRIHA and IGBC have been considered for comparison. Based on the respective technical manuals of BREEAM, LEED, IGBC, and GRIHA assessment systems and related publications, the categories and criteria are compared in order to diagnose the significant similarities and differences underlying in them and thereby establishing the criteria and sub-criteria for developing a new assessment method. While diagnosing the similarities and differences, the study emphasized on potential and possible criteria to be considered in developing countries like India. The specific purpose to compare these tools is to check whether these assessment criteria and attributes are transferrable and adaptable to suit the circumstances and the state of affairs in India (Table 4.1).

Table 4.2 summaries, the components, features, and criteria compares the existing assessment tools (BREEAM, LEED, IGBC, and GRIHA) to understand the depth of each of the criteria and their related attributes (see Table 4.2). The symbol '√' represents that the criteria are included in the respective assessment tool, whereas 'x' represents that it does not. Some of the criteria which contribute to building sustainability are neither included in IGBC nor GRIHA. Similarly, the attributes which are included in IGBC are not included in GRIHA and vice-a-vice, for example, ventilation, CO_2 emissions, and material efficiency. Irrespective of these, some criteria like topographical consideration, climatic conditions, local context, and regional variations are not at all considered.

For instance, energy is considered as a key category for all assessment methods and is given the highest possible points. BREEAM measures Building Energy Performance (BEP) along with CO_2 emission reductions with the target of net zero emissions. On the other hand, LEED emphasizes reduction of energy costs for BEP rather than CO_2 emissions which is in line with the standards of American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE). LEED mainly focuses on renewable energy utilization for measuring BEP and energy optimization. But energy monitoring and enhanced commissioning are not considered in GRIHA rating system.

The three assessment methods (LEED, BREEAM, and GRIHA), evaluate most of the major water quality and quantity parameters. Indoor water use reduction, potable water use reduction, water recycle and reuse, wastewater treatment and efficient landscaping are the common criteria considered in all the three rating tools. Water leak detection and water metering are considered as important criteria but they are considered in GRIHA for water efficiency evaluation.

Waste criteria and their parameters are integral to all three assessment methods. Within this broad criterion, waste management and recycling emerge as the most important parameters, due to their importance in minimizing the negative impacts of waste generation for humans and the surrounding environment. Construction materials is another important element of environmental assessment method due to the impact of material consumption on building users and environment. BREEAM and LEED emphasize sourcing of raw materials, but it is not considered in GRIHA. Renovation of abandoned buildings is considered in LEED, but not considered in GRIHA evaluation criteria for assessment.

Indoor environmental quality (IEQ) is considered as a key objective for all building assessment methods. BREEAM and GRIHA include this category under Health and Well-being section. LEED assesses this category through low-emitting materials, indoor air quality, and quality views. Similarly, BREEAM assesses this category through visual comfort, the impact of refrigerants and noise pollution. GRIHA assesses this category through air quality, low-VOC paints, sanitation/safety facilities, but at the same time omits visual comfort, quality views, and hazards in its criteria. Tobacco smoke control, pollution, thermal comfort, and air quality are commonly considered in all three assessment methods.

Sustainable site categories focus mainly on-site selection, site reuse, and site protection, with the aim of reducing soil erosion and improving site conditions. BREEAM addresses sustainable sites with its Land use and ecology category. BREEAM considers environmental protection as its primary parameter, while in case of LEED and GRIHA, the sustainable site is highly important. Light pollution reduction and joint use of facilities are considered in LEED but not considered in GRIHA. All the tools evaluated in this study offer credits to encourage and support sustainability measures. BREEAM considers Management as a separate category for its assessment, while LEED distributes management parameters across several assessment categories. BREEAM covers sustainable management principles more comprehensively than LEED. Transportation is considered as a separate category in LEED and BREEAM. The LEED addresses transportation with its Location and Transportation criterion with 16 possible points whereas, BREEAM, assesses with 13 possible points. From the observations, it was found that the criterion Transportation and Management were not considered in GRIHA for environmental assessment.

Table 4.2 Comparison of criteria based on existing Assessment tools

Criteria	Attributes	Factors	BREEA	LEE	IGBC	GRIHA
Sustainable site and ecology	Construction site	Selection of site	√	√	√	√
		Protection of site	√	√	√	√
	Ecological value	Land contamination	√	√	√	√
		Mitigating ecological impact	√	√	√	√
		Balancing site ecology	√	√	√	√
		Protecting biodiversity	√	√	√	√
	Transport	Ease of accessibility	√	√	√	√
		Developing density	√	√	√	X
		Intercommunity network	√	√	√	X
		Safety of pedestrian	√	√	X	X
		Car parking facility	√	√	√	X
Energy efficiency	Energy performance	HVAC	√	√	√	√
		Rate of ventilation	√	√	√	X
		Internal and external lighting	√	√	√	√
		Provision of hot water	√	√	√	√
		Heat transmission	√	√	X	X
		Renewable technology on	√	√	√	√
		Monitoring energy	√	√	√	X
		Energy saving	√	√	√	√
		CO_2 Strategy	√	√	√	X
Water efficiency and water management	Water	Reducing the consumption of water	√	√	√	√
		Harvesting water	√	√	√	√
		Recycling of water	√	√	√	√
		Innovative water recycling	√	√	√	√
		Water conservation technique	√	√	√	√
		Water irrigation technique	√	√	√	√
		Groundwater recharge	√	√	√	√
Material	Material category	Low impact environment material	√	√	√	√
		Use of non- renewable resources	√	√	X	X
		Material reuse	√	√	√	X
		Using innovative technology for non- structure	√	√	√	X
		Insulating component	√	√	X	X
		Material finishing	√	√	√	X
		Local resources utility	√	X	√	X
		The efficiency of material over LC	√	√	X	X
Pollution and risk		Global warming potential for refrigerant	√	√	√	X

	Emissions and disaster	Noise pollution	√	√	√	X
		Preventing pollution leaks	√	X	√	X
		Water pollution	√	√	X	X
		Effect of heat island	√	√	√	X
		Source of NO_x emission	√	√	X	X
		Carbon emission	√	√	√	X
		Fire safety	√	√	X	√
		Natural Disaster	√	√	X	X
Indoor environment quality	Noise and acoustics	Level of noise emitting	√	√	X	√
		Insulation to sound source	√	X	X	√
		Absorption of sound acoustics	√	X	X	√
	Lighting and illumination	Active lighting	√	√	√	√
		Lighting control	√	√	√	√
		Open view	√	√	√	X
		Measuring and control on glaring	√	√	X	X
		Level of illumination	√	√	√	X
		Daylight factor	√	√	√	X
	Ventilation	Natural ventilation	√	√	√	√
		Type of ventilation	√	√	√	√
		Supply of purified and fresh air	√	√	√	√
		Air monitoring sensor	√	√	√	X
		Monitoring on carbon emission	√	√	√	
	Contamination level	Unstable compounds	√	√	√	√
		Pollution of electromagnetic	X	X	X	X
		Level of microbiological content	√	√	X	X
	Thermal comfort	Controlling zone	√	√	X	X
		Heating, cooling, humidity, vapor control, and comfort	√	√	√	√

This comparative discussion enabled identify, the potentially viable criteria which really suits the context. This also facilitates to identify the drawbacks and shortcomings in the existing rating system for its compatibility. Keeping in view the unique local context, climate conditions, culture, topography, and ethical aspects prevailing in India, the most prominent sustainable criteria and their related sub-criteria are identified. The identified list is then refined and was utilized to develop priorities and weights through quantitative research methods and Multi-criteria Decision Making (MCDM) Methods. In the refining phase, the not so relevant criteria are excluded and eight indicators and their relevant sub-indicators were identified.

4.7 Delphi Technique

In the early 1950's, the US defense industry developed the Delphi method (Mahmoudkelaye et al., 2017) to achieve some confidential objectives. The technique involves obtaining reliable consensus opinions from a group of experts, through a number of rounds using structured questionnaires and interviews. To develop communication and seek an opinion from a group of experts to resolve a complex issue, the Delphi technique is preferred (Linstone et al.1975). It is an organized approach wherein, it reaches consensus and stable decisions from a set of opinions on a subjective issue. The consistency and robustness of the techniques lie in the principles adopted by it (Adler and Ziglio, 1996) and are as follows.

(i) Iteration:

The Delphi technique is a series of responses obtained from the participants. A set of questions are posed to the panelists for their responses. Based on the responses, the coordinator will again pose a subsequent series of questions. This iteration process allows the participants to view the previous response given by the rest of the panelists, which makes them re-think and give consensus decision judgment.

(ii) Anonymity:

In order to eliminate the effects caused by influence, experience, position, and dependency of the co-panelists, the responsibility of the coordinator will be to maintain the obscurity of the participants throughout the process.

(iii) Controlled feedback:

Once the coordinator receives the responses from the panelists, he/she will able to carry out the next analysis for further development of the process. This controlled feedback will avoid heated arguments, debates, and misperception. This facilitates the smooth process with increased coordination and cooperation of the issue.

(iv) Statistical response:

The use of statistical analysis is recommended to reflect the overall group responses from the Delphi method. This will ultimately give conformity and reasonability for the obtained results.

These salient features of the Delphi method are considered in the present study, to identify the multi-dimensional sustainable criteria for developing a comprehensive and effective assessment tool. This consensus-based approach based on the questionnaire is the most appropriate approach to reach an agreement for establishing the criteria (Ding, 2008; Chew and Das, 2008). The influence of brainstorming, narrowing down and prioritizing the options make Delphi method to identify and establish the criteria. The outcomes of each round are bridged and the process is repeated until a stable and balanced opinion/reaction is observed. The collection of data from the Delphi method is a repetitive process, and obtaining the precise and consensus data depends on the level of question asked in the subsequent rounds. Once the coordinator feels that the problem has received consensus judgment on the issue, the number of iterations can be reduced. So, it is not essential to conduct a specific number of iterations (Hasson and Keeney, 2011).

In the present study, the panelists were selected based on their knowledge, capability, qualification, and experience in the domain of the problem examination. These are professional and informed local experts from public and private organizations, academicians, consultants, designers, architects, and others. The following are the guidelines:

- Academician having expert knowledge and awareness in sustainable construction.
- Certified/Accredited professional from Sustainable assessment organization
- Decision makers from the industry with knowledge on sustainable principles and practices
- Practicing Expert for assessing the performance for criteria practically and adopt the resultant methodology
- Habitats of sustainable buildings

The structured questionnaire is one of the most extensively used data collection technique by conducting surveys in order to find out various opinions, facts and views. The questionnaire design was first tested through a pilot study for its accuracy and then based on that, the comments were incorporated into the final questionnaire. The Delphi technique is performed with the help of six experts having a minimum 20 years of experience in the domain of sustainable construction, each belonging to Academicians, Engineers, Designers, Architects, Consultants, and Others. Before implementing the Delphi technique, the potential criteria have been compiled from existing tools (BREEAM, LEED, IGBC, and GRIHA), policies and guidelines to understand the depth of each of the criteria and their related attributes (Table 4.3). With the help of these criteria and attributes, the questionnaire is prepared and designed to respond on a five-point Likert scale, where “1” represents low importance and “5” represents high importance (Appendix A).

Table 4.3 Overview of the list of identified criteria and Sub-criteria

Code	***Criteria***	***Attributes***
WE (C1)	Water efficiency	Water monitoring and leak detection (SC1)
		Building water use reduction (SC2)
		Recycling of water (SC3)
		Reuse of water (SC4)
		Grey water recycling (SC5)
		Rainwater management (SC6)
		Reduction in Landscape water requirement (SC7)
MW (C2)	Materials and waste management	Low-energy materials (SC8)
		High-performance material (SC9)
		Material replacement (SC10)
		Regionally available materials (SC11)
		Recycled and reuse of materials (SC12)
		Material Efficiency (SC13)
		Energy Efficiency (SC14)
		Use of salvaged, refurbished material (SC15)
		Responsible sourcing (SC16)
		Efficient waste management (SC17)
HW (C3)	Health and well-being	Visual and thermal comfort (SC18)
		Indoor air quality (SC19)
		Ventilation (SC20)
		Lighting (SC21)
		Thermal comfort (SC22)
		Water quality & water pollution (SC23)
		Outdoor & indoor noise levels (SC24)
		Reduce air pollution (SC25)
		Sanitation/Safety facilities & Accessibility (SC26)
		Habitant Satisfaction (SC27)
		Minimize ozone depletion (SC28)
EE (C4)	Energy efficiency	Renewable energy production (SC29)
		Energy efficient appliances (SC30)
		Energy monitoring (SC31)
		Reduction in energy consumption associated with interior lighting (SC32)
		Adequate lighting (SC33)
		Refrigerant management/Green power (SC34)
		Solar water heating (SC35)
		Optimize energy performance (SC36)
		Energy Efficient Vertical transportation systems (SC37)
SS (C5)	Sustainable sites	Site selection (SC38)
		Protect or restore habitat (SC39)
		Heat island reduction (SC40)
		Open space (SC41)
		Reduced light pollution (SC42)
		Conservation of soil surrounding the building (SC43)
		Stormwater design (SC44)
		Site improvement plan (SC45)

		Protect ecosystem and preserve biodiversity (SC46)
SW (C6)	Social welfare	Knowledge and Awareness towards sustainability (SC47)
		Local Economic Development (SC48)
		Development of Skill (SC49)
		Employment opportunities (SC50)
		Efficient ventilation (SC51)
		Design for durability (SC52)
		Protect cultural heritage (SC53)
T (C7)	Transportation	Public transport accessibility (SC54)
		Use of Bicycles (SC55)
		Proximity to amenities (SC56)
		Environmentally friendly pavements at the building site (SC57)
		Use of solar power vehicles (SC58)
		Innovation in transportation (SC59)
		Reduced parking footprint (SC60)
M (C8)	Management	Managing the balance between the building and its immediate surrounding (SC61)
		Managing fire prevention facilities (SC62)
		Life cycle costing (SC63)
		Integrated design process (SC64)
		Responsible construction practices (SC65)
		Construction site improvements (SC66)
		Preventing the reckless dumping of polythene products at the building site (SC67)
		Stakeholder participation (SC68)

4.8 Relative Importance Index

The questionnaire was designed in such a way that the panelists were asked to assess the significance of each and every attribute for establishing sustainable building assessment. To determine the relevant attributes for building assessment, the collected data has been evaluated using the Relative Importance Index (RII) by Equation 4.6

$$RII = \frac{\sum_{i=1}^{N} P_i R_i}{N \times n} \quad \text{(Eq 4.6)}$$

Where, RII = Relative Importance Index;

P_i = Respondent's rating;

R_i = Number of respondents placing identical weighting/rating;

N = Sample size;

n = Highest attainable score;

The attributes whose RII value is more than or equal to 0.7 has been screened out for selecting the most significant parameters to assess the performance of the building (Table 4.4).

Table 4.4 Relative Importance Index (RII) of the attribute with regard to criteria

Criteria	*Attributes*	*Academician*	*Designer*	*Architect*	*Consultant*	*Engineer*	*Others*	RII
C1	SC1	5	4	3	4	5	4	**0.833**
	SC2	5	4	3	4	5	4	**0.833**
	SC3	4	4	5	4	3	3	**0.767**
	SC4	3	5	4	5	3	2	**0.733**
	SC5	3	2	4	3	2	1	**0.500**
	SC6	4	4	5	3	4	3	**0.767**
	SC7	3	4	5	4	3	3	**0.733**
C2	SC8	4	3	4	5	3	3	**0.733**
	SC9	4	5	4	3	2	1	**0.633**
	SC10	4	4	3	4	2	2	**0.633**
	SC11	4	3	4	4	3	4	**0.733**
	SC12	4	3	5	4	3	4	**0.767**
	SC13	4	3	5	4	1	2	**0.633**
	SC14	3	4	4	3	2	1	**0.567**
	SC15	4	3	4	1	1	1	**0.467**
	SC16	4	5	4	3	4	2	**0.733**
	SC17	5	3	3	4	4	3	**0.733**
C3	SC18	4	3	4	3	4	3	**0.700**
	SC19	4	4	3	3	3	3	**0.667**
	SC20	4	4	4	4	4	4	**0.800**
	SC21	4	4	4	4	4	3	**0.767**
	SC22	4	4	3	5	4	3	**0.767**
	SC23	4	3	4	4	4	3	**0.733**
	SC24	3	4	4	3	4	3	**0.700**
	SC25	4	3	3	3	4	1	**0.600**
	SC26	5	4	4	3	4	3	**0.767**
	SC27	3	4	3	4	2	2	**0.600**
	SC28	4	3	3	4	3	5	**0.733**
C4	SC29	5	3	4	4	4	3	**0.767**
	SC30	5	3	3	4	3	4	**0.733**
	SC31	5	4	3	3	4	3	**0.733**
	SC32	3	3	3	3	4	3	**0.633**
	SC33	4	4	3	4	3	3	**0.700**
	SC34	3	3	2	3	3	2	**0.533**
	SC35	4	3	4	4	4	3	**0.733**
	SC36	4	3	3	4	3	3	**0.667**
	SC37	4	3	4	4	3	3	**0.700**
C5	SC38	5	3	2	5	4	3	**0.733**
	SC39	4	5	3	4	3	2	**0.700**
	SC40	3	5	5	4	4	3	**0.800**
	SC41	4	2	5	4	3	3	**0.700**
	SC42	4	4	4	4	4	3	**0.767**
	SC43	4	3	5	4	4	2	**0.733**
	SC44	5	2	1	1	2	3	**0.467**
	SC45	5	2	1	4	5	1	**0.600**
	SC46	3	4	3	3	3	3	**0.633**
C6	SC47	5	4	3	4	4	4	**0.800**
	SC48	4	2	3	4	2	2	**0.567**
	SC49	5	3	4	1	2	3	**0.600**
	SC50	3	3	2	1	4	2	**0.500**
	SC51	3	5	5	4	3	2	**0.733**
	SC52	5	5	3	4	3	3	**0.767**
	SC53	4	2	1	3	5	4	**0.633**
C7	SC54	3	4	3	5	3	3	**0.700**
	SC55	4	4	4	4	4	2	**0.733**

	SC56	4	4	3	4	3	4	**0.733**
	SC57	5	4	3	4	4	4	**0.800**
	SC58	4	4	3	2	2	2	**0.567**
	SC59	4	4	2	4	1	1	**0.533**
	SC60	2	4	4	4	4	5	**0.767**
C8	SC61	4	2	3	4	5	5	**0.767**
	SC62	4	4	3	4	5	3	**0.767**
	SC63	3	3	2	4	3	3	**0.600**
	SC64	4	5	3	3	2	3	**0.667**
	SC65	2	2	3	4	2	2	**0.500**
	SC66	2	3	4	2	3	1	**0.500**
	SC67	3	4	3	4	4	4	**0.733**
	SC68	3	2	3	3	4	3	**0.600**

The attributes identified are then categorized into main criteria. The grouping of attributes into the main criteria is carried out based on the specific context and common implication followed by the existing assessment tools. This facilitates comparing the importance/weight given to the criteria in various existing tools. The process of identifying, evaluating and refining attributes and categorizing into criteria and then into indicator is a Bottom-up approach. The bottom-up approach involving a number of stages/levels forms a complex hierarchy structure (Fig 4.6).

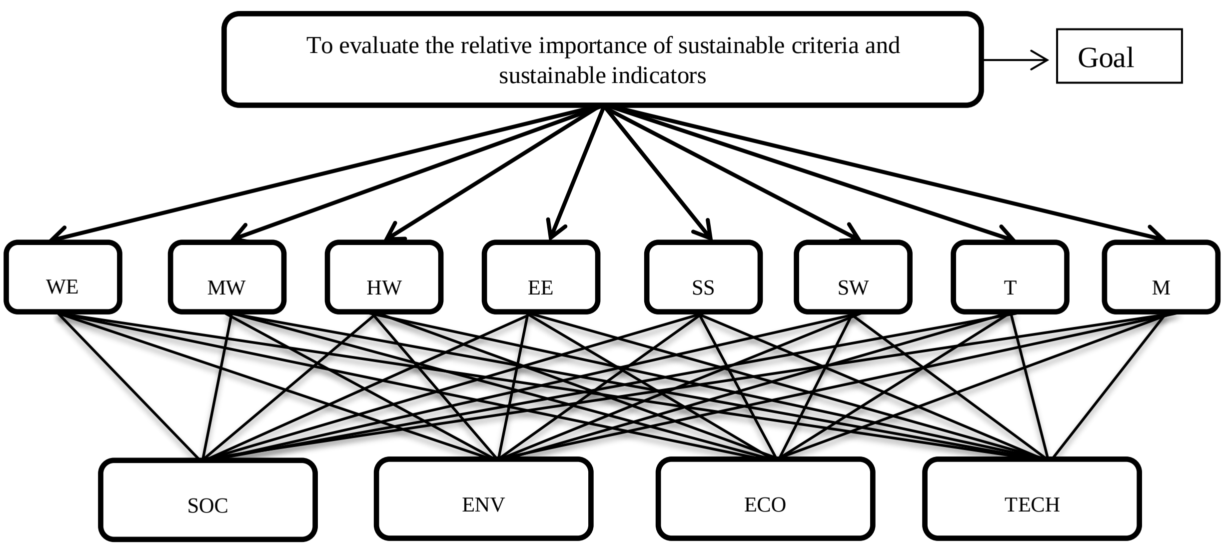


Fig 4.6 Hierarchical structure of Sustainable Criteria with respect to SEET Indicators

The ultimate criteria and attributes for sustainable building assessment are determined as shown in Table 4.5

Table 4.5 Most prominent sustainable criteria and sub-criteria for the Indian context

Code	Criteria	Attributes
WE	Water Efficiency	Water monitoring and leak detection (A1) Building water use reduction (A2) Recycle and reuse of water (A3) Rainwater management (A4) Reduction in landscape water requirement (A5)
MW	Materials and Waste management	Low-energy materials (B1) Regionally available materials (B2) Recycled and re-use materials (B3) Responsible sourcing (B4) Efficient waste management (B5)
HW	Health and Well-being	Water quality & water pollution (C1) Outdoor & indoor noise levels (C2) Sanitation/Safety facilities & Accessibility (C3) Minimize ozone depletion (C4)
EE	Energy Efficiency	Renewable energy production (D1) Energy efficient appliances (D2) Energy monitoring (D3) Reduction in energy consumption associated with interior lighting (D4) Adequate Daylight (D5) Energy efficient vertical transportation systems (D6)
SS	Sustainable Sites	Site selection (E1) Protect or restore habitat (E2) Heat island reduction (E3) Open space (E4) Light Pollution (E5) Efficient ventilation (E6) Conservation of soil surrounding the building (E7)
SW	Social Welfare	Knowledge and Awareness towards sustainability (F1) Local Economic Development (F2) Design for durability (F3)
T	Transportation	Public transport accessibility (G1) Use of Bicycles (G2) Proximity to amenities (G3) Environmentally friendly pavements at the building site (G4) Reduced parking footprint (G5)
M	Management	Managing the balance between the building and its immediate surrounding (H1) Managing fire prevention facilities (H2) Preventing the reckless dumping of polythene products at the building site (H3)

4.9 Analytical Hierarchy Process (AHP)

The AHP is a Multi-Criteria Decision Making (MCDM) process used to evaluate both qualitative and quantitative issues (Alwaer et al., 2010), in a systematic and logical way to determine the significance of a set of dependent criteria. The relative indicators for a single goal are adopted in this study for analyzing the problem. This involves splitting up of a decision problem into a number of hierarchy levels, to enable them to analyze independently. To evaluate the building performance based on indicators and criteria, relative weights are determined using the concept of pairwise comparison to eliminate bias existing in the human judgment. The human perception involved with uncertainty and ambiguity can be resolved with the fuzzy logic concept. In the present study, to establish the interrelationship among the criteria, indicators, and criteria to indicators, Fuzzy AHP has been employed in decision making. To determine the priority weights of criteria towards each of the indicators, pair-wise comparison of the criteria and indicators is performed for each individual judgments and then averaged. The formation of the questionnaire to get responses in AHP strategy is quite intricate due to its reciprocity in the matrix development and hence is widely criticized (Al-Jebouri et al., 2017). To receive wide responses from all the domains of civil engineering, the 7-point Likert scale is proposed to be converted into Saaty's scale as shown in Table 4.6. This approach facilitates experts to participate in large numbers giving less/minimum time to respond.

Table 4.6 Conversion of Likert scale 1-7 to 1-9 Saaty's scale

Saaty's Scale		**Converted Scale**	
Relative Intensity	**Definition**	**Comparative scale**	**Importance/Preference**
1	Of equal importance	7-7	The difference of values =0
3 (or) 1/3	Slightly more value	1-2; 2-3; 3-4; 4-5; 5-6; 6-7	Difference of values =1 (or) -1
5 (or) 1/5	Essential or strong value	1-3; 2-4; 3-5; 4-6; 5-7	Difference of values =2 (or) -2
7 (or) 1/7	Very strong value	1-4; 1-5; 2-5; 2-6; 3-7; 4-7	Difference of values = (3 or 4) or (-3 or -4)
9 (or) 1/9	Extreme value	1-7; 2-7	Difference of values = (5 or 6) or (-5 or -6)

4.9.1 Data Collection

The data is collected using questionnaire response and personal interviews. The questionnaire survey is designed and formulated in such a way that the importance of each of the identified criteria is measured towards the four indicators (SEET). The respondents were invited to assess the level of importance of criteria and indicators by assigning a score on the seven (7) point Likert scale (Appendix B). A score of '1' indicates as 'not important' whereas, '7' indicates 'highly important'. Professionals from all domains of Civil Engineering are invited and classified them Academicians, Contractors, Engineers, Designers, Consultants, Architects, and Others.

Based on the sample size calculation (n) from Equation 4.7(a & b) the sample size is calculated. The population size (N) considered as 147 experts, who were contacted. Considering a confidence level of 95% the corresponding z-score (z) is 1.96 and Population proportion (p) 0.5; margin of error (∊) as 10%. The sample size (n) is calculated to be 58.

(If population size, N is unknown) $n = \frac{z^2 * p(1-p)}{\epsilon^2}$ (Eq. 4.7a)

(If population size, N is known) $n' = \frac{n}{1+\frac{z^2 * p(1-p)}{\epsilon^2 N}}$ (Eq. 4.7b)

Among 147 professionals, a total of 96 professionals responded, having an experience between 1 – 20 years, in survey and their details are as follows:

- 32 Academicians
- 22 Client/engineer
- 12 Contractors
- 7 Designers
- 8 Architects
- 7 Consultants
- 8 Others with the knowledge in this field.

4.9.1.1 Data Consistency using Cronbach's Alpha

Among the 96 responses, incomplete data and data which is not reliable to consider has been neglected. A total of 58 reliable and complete responses were selected for further investigation. To observe the consistency of collected data, a statistical analysis was conducted to expedite the results using Cronbach's alpha coefficient (Table 4.7).

4.9.1.1 Cronbach's Alpha Coefficient

The internal consistency of the collected data with multiple responses and opinions can be measured using Cronbach's alpha, within the set of closely related items of the group. It is considered to be a measure of scale reliability. Technically, Cronbach's alpha is not a statistical test, it is a coefficient of reliability or consistency (Tavakol & Dennick, 2011). In other words, this measures how consistently individuals have correlated the number of items within the given scale in a group (Cronbach & Shavelson, 2004).

Cronbach's alpha is a function of a number of items and the average intra-class correlation among the items. Cronbach's alpha for a given set of data items in a group can be calculated by the following Equation 4.8.

$$\alpha = \frac{N \times c}{v + (N-1) \times c} \qquad \text{(Eq 4.8)}$$

N is the number of items, c is the average inter-item covariance among the items and v is the average variance. In general, the alpha score of more than 0.70 is considered acceptable while some authors proposed values between 0.80 and 0.90 (Tavakol & Dennick, 2011).

In the present study, the Cronbach's alpha was calculated for four different groups (namely, Social, Environmental, Economic, Technological) from the information provided by 58 valid respondents and is shown in Table 4.7 In all the groups, the **α** values were found to be more than 0.80. Thus, the data provided is found to be reliable and was of good quality.

Table 4.7 Cronbach's Alpha Coefficient for SEET criteria

Criteria code	Social (α = 0.854)			Environmental (α = 0.820)			Economic (α = 0.811)			Technological (α = 0.861)		
	Scale Mean if (I_i) Deleted	Scale Variance if (I_i) Deleted	Cronbach's Alpha if (I_i) Deleted	Scale Mean if (I_i) Deleted	Scale Variance if (I_i) Deleted	Cronbach's Alpha if (I_i) Deleted	Scale Mean if (I_i) Deleted	Scale Variance if (I_i) Deleted	Cronbach's Alpha if (I_i) Deleted	Scale Mean if (I_i) Deleted	Scale Variance if (I_i) Deleted	Cronbach's Alpha if (I_i) Deleted
WE	39.672	42.540	0.864	41.328	38.680	0.818	37.828	52.040	0.839	40.000	44.211	0.877
MW	39.052	43.173	0.850	41.086	36.712	0.799	37.483	45.131	0.804	39.914	42.887	0.853
HW	39.276	42.168	0.848	41.362	36.902	0.801	37.086	48.536	0.805	40.086	42.291	0.853
EE	39.397	43.121	0.850	41.276	39.080	0.816	36.948	48.436	0.815	39.672	42.049	0.849
SS	39.310	43.867	0.860	41.810	42.016	0.854	37.207	48.377	0.803	39.931	43.644	0.863
SW	39.517	41.026	0.844	41.397	35.226	0.794	37.000	44.947	0.801	39.707	42.316	0.849
T	39.207	43.360	0.849	41.397	36.980	0.799	37.328	49.522	0.813	40.172	43.514	0.867
M	39.328	45.733	0.865	42.362	44.761	0.883	36.500	48.254	0.807	39.741	46.616	0.873

4.10. Determining Relative Weights

To determine the relative importance of sustainable criteria and indicators, the present study explored the use of Fuzzy AHP method. It requires a hierarchical structure that descends from the primary goal to category and sub-category in subsequent levels. The method requires three steps: 1) Structuring the hierarchy, 2) Establishing pairwise comparison matrix, 3) Weight and priority analysis (Saaty, 2008). The pairwise comparison focuses on subjective judgments to calculate the weight vector using the principles of the eigenvector, and finally evaluate the relative weights with respect to SEET indicators. The approach evaluates the interrelationship between sustainable indicators and criteria and is established to understand the relative performance towards assessing building sustainability.

When multiple decision makers participate in the judgments, the aggregation of information can be of two ways: a) Aggregation of Individual Judgements (AIJ), firstly, the individual judgments from the survey are aggregated and later worked on pairwise comparison to get an aggregated weight; b) Aggregation of Individual Priorities (AIP), here unlike AIJ, for each respondent, the individual priorities are calculated and aggregated using arithmetic mean to get a single weight.

In the present study, through AIP, weights for sustainable indicators have been evaluated for 58 respondents with respect to four SEET criteria forming 8 x 8 matrix (i.e., 58 x 4 x 8 x 8). Similarly, the weights for sustainable criteria have been evaluated (i.e., 58 x 8 x 4 x 4). In order to eliminate the vagueness and uncertainty in the perception of judgments by decision makers, the fuzzy approach has been employed in addition to AHP pairwise comparison, which is a Hybrid Multi-Criterion Decision Method. Fuzzy AHP embeds the fuzzy theory to basic AHP. It is a widely used decision-making tool in various multi-criteria decision-making problems.

4.11 Data Analysis to determine interrelation among criteria and indicators

The data obtained on the importance of sustainable indicators considering SEET criteria is utilized for statistical calculations as illustrated in Table 4.8. For example, Designers have given higher importance to Indicator (I_1) with a Mean (M) of 6.50 and Standard Deviation (SD) of 0.72 among all the experts. Similarly, the academicians have given less importance to I_5 with an M of 5.15 and SD of 1.09. This illustrates that different expert groups have allocated a different weighted score to indicators which enables us to understand the perceptions of different expert groups in assessing the weights of sustainable indicators. The relative weights of the indicators with respect to criteria and vice versa are evaluated using F-AHP and is shown in Fig 4.9.

Table 4.8 Importance of Sustainable Indicators w.r.t expert domains

Indicator code	All (N=58)		Academicians (N=18)		Engineers (N=16)		Consultants (N=05)		Designers (N=03)		Architects (N=05)		Contractors (N=08)		Others (N=03)	
	Mean	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*	*Mean*	*Std Dev*
WE	5.41	1.40	5.31	1.39	5.27	1.44	5.15	2.22	6.50	0.72	5.40	1.28	5.25	1.20	5.58	0.87
MW	5.74	1.33	5.46	1.39	5.66	1.43	6.40	0.75	6.25	0.83	5.28	1.48	5.44	1.32	6.33	0.95
HW	5.67	1.28	5.32	1.59	5.88	1.22	5.45	1.06	6.42	0.72	5.28	1.34	5.47	1.13	6.00	0.67
EE	5.80	1.28	5.44	1.36	5.94	1.30	5.95	1.28	6.17	0.89	5.45	1.57	5.63	1.38	5.83	1.17
SS	5.56	1.31	5.15	1.09	5.56	1.44	6.10	0.87	6.50	0.58	5.40	1.60	5.31	1.78	6.17	1.10
SW	5.72	1.39	5.46	1.58	5.95	1.32	5.75	1.32	6.08	1.06	5.23	1.66	5.41	1.57	6.00	1.16
T	5.59	1.26	5.29	1.22	5.78	1.33	5.70	0.75	6.42	0.81	5.20	1.36	5.41	1.20	5.50	1.02
M	5.64	1.29	5.36	1.31	5.84	1.23	6.00	0.95	5.50	0.93	5.40	1.30	5.38	1.37	5.42	1.30

4.12 Procedure to evaluate the relative weights using Fuzzy AHP (*Economic indicator and for one respondent*)

The following steps are involved in assessing the weights of criteria and indicators using Fuzzy AHP.

Step 1: Compute the fuzzy pairwise comparison matrix using Equation 4.9, where $\tilde{d}_{ij}^{k}$ indicates the fuzzified preference of ith indicator over jth indicator by the kth decision maker for SEET indicator using fuzzy triangular numbers shown in Table 4.9.

$$\widetilde{A^k} = [\tilde{d}_{ij}^{k}] = \begin{vmatrix} 1 & d_{12} & \cdots & d_{1n} \\ \frac{1}{d_{12}} & 1 & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{d_{1n}} & \frac{1}{d_{2n}} & \ldots & 1 \end{vmatrix} \qquad \text{(Eq. 4.9)}$$

Table 4.9 Triangular fuzzy pairwise comparison decision matrix for Economic Criteria

	WE	MW	HW	EE	SS	SW	T	M
WE	(1,1,1)	(0.25,0.33,0.5)	(4,5,6)	(4,5,6)	(2,3,4)	(1,1,1)	(1,1,1)	(6,7,8)
MW	(2,3,4)	(1,1,1)	(6,7,8)	(6,7,8)	(4,5,6)	(2,3,4)	(2,3,4)	(6,7,8)
HW	(0.167,0.2,0.25)	(0.125,0.14,0.167)	(1,1,1)	(1,1,1)	(0.25,0.33,0.5)	(0.167,0.2,0.25)	(0.167,0.2,0.25)	(2,3,4)
EE	(0.167,0.2,0.25)	(0.125,0.14,0.167)	(1,1,1)	(1,1,1)	(0.25,0.33,0.5)	(0.167,0.2,0.25)	(0.167,0.2,0.25)	(2,3,4)
SS	(0.25,0.33,0.5)	(0.167,0.2,0.25)	(2,3,4)	(2,3,4)	(1,1,1)	(0.25,0.33,0.5)	(0.25,0.33,0.5)	(4,5,6)
SW	(1,1,1)	(0.25,0.33,0.5)	(4,5,6)	(4,5,6)	(2,3,4)	(1,1,1)	(1,1,1)	(6,7,8)
T	(1,1,1)	(0.25,0.33,0.5)	(4,5,6)	(4,5,6)	(2,3,4)	(1,1,1)	(1,1,1)	(6,7,8)
M	(0.125,0.14,0.16)	(0.125,0.14,0.167)	(0.25,0.33,0.5)	(0.25,0.33,0.5)	(0.167,0.2,0.25)	(0.125,0.14,0.167)	(0.125,0.14,0.167)	(1,1,1)

Step 2: Compute the triangular fuzzy numbers using minimum, geometric mean and maximum concepts (Equation 4.10) shown in Table 4.10. Here, $\tilde{r}_i$ represents triangular values, where $\tilde{a}_{ij}$, $\tilde{b}_{ij}$, and $\tilde{c}_{ij}$ represents the degree of belonging or membership value for a triangular fuzzy function.

$$\tilde{r}_i = \{[\min(\tilde{a}_{ij})], [(\prod_{j=1}^{n}(\tilde{b}_{ij}))^{1/n}], [\max(\tilde{c}_{ij})]\} \text{; where j = 1, 2… n} \qquad \text{(Eq. 4.10)}$$

Table 4.10 Fuzzy triangular decision matrix

	WE	*MW*	*HW*	*EE*	*SS*	*SW*	*T*	*M*
Fuzzy group judgements	(0.25, 1.90, 8.00)	(1.00, 8.83, 8.00)	(0.13, 0.43, 4.00)	(0.13, 0.43, 4.00)	(0.17, 0.87, 6.00)	(0.25, 1.90, 8.00)	(0.25, 1.90, 8.00)	(0.13, 0.23, 10.00)

Step 3: The fuzzy weights of each indicator can be found by aggregating the fuzzy rating (Equation 4.11) explained in the following next 3 sub-steps.

Step 3a: Find the vector summation of each $\tilde{r}_i$ using Equation 4.11 (Table 4.12).

$$\tilde{r}_i = \sum_{i=1}^{m}(\min(\tilde{a}_{ij})), \sum_{i=1}^{m}(\prod_{j=1}^{n}(\tilde{b}_{ij})), \sum_{i=1}^{m}(\max(\tilde{c}_{ij}))$$

where i=1, 2,… m (Eq.4.11)

Table 4.11 Vector summation decision matrix

	Fuzzy Triangular Numbers		
Vector Summation of ($\tilde{r}_i$)	(2.292)	(11.499)	(47.000)

Step 3b: Find the (-1) power of the summation vector and then replace the fuzzy triangular number an increasing order (Table 4.12).

Table 4.12 Reverse and increasing order of Vector summation decision matrix

	Fuzzy Triangular Numbers		
Reverse Vector Summation of ($1/\tilde{r}_i$)	(0.436)	(0.087)	(0.021)
Increasing Vector Summation of ($1/\tilde{r}_i$)	(0.021)	(0.087)	(0.436)

Step 3c: To find the fuzzy weight of indicator ($\widetilde{w}_i$), multiply each $\tilde{r}_i$ with the increasing vector summation decision matrix using Equation 4.12 (Table 4.13).

$$\widetilde{w}_i = \tilde{r}_1 * (\tilde{r}_1 + \tilde{r}_2 + \tilde{r}_3 + \cdots + \tilde{r}_n)^{-1}$$

$$= (aw_i, bw_i, cw_i) \qquad \text{(Eq.4.12)}$$

Table 4.13 Triangular Fuzzy weight of Criteria

	WE	***MW***	***HW***	***EE***	***SS***	***SW***	***T***	***M***
Fuzzy Weights ($\widetilde{w}_i$)	(0.005, 0.166, 3.490)	(0.021, 0.333, 3.490)	(0.003, 0.037, 1.745)	(0.003, 0.037, 1.745)	(0.004, 0.076, 2.618)	(0.005, 0.166, 3.490)	(0.005, 0.166, 3.490)	(0.003, 0.020, 0.436)

Step 4: Since $\widetilde{w}_i$ are in fuzzy triangular numbers, they are de-fuzzified by Centre of Area method proposed by Wang and Wang (2014) using the Equation 4.13 (Table 4.14).

$$M_i = \frac{aw_i + bw_i + cw_i}{3} \qquad \text{(Eq. 4.13)}$$

Table 4.14 De-fuzzified weights of Criteria

	WE	*MW*	*HW*	*EE*	*SS*	*SW*	*T*	*M*
De-fuzzified Weights (M_i)	(1.220)	(1.282)	(0.595)	(0.595)	(0.899)	(1.220)	(1.220)	(0.153)

Step 5: The M_i is a non-fuzzy number and the normalized values are evaluated using Equation 4.14 (Table 4.15).

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \qquad \text{(Eq. 4.14)}$$

Table 4.15 Normalized De-fuzzified weights of Criteria

	WE	*MW*	*HW*	*EE*	*SS*	*SW*	*T*	*M*
Normalized Weights (M_i)	(0.170)	(0.178)	(0.083)	(0.083)	(0.125)	(0.170)	(0.170)	(0.021)

The relative weights of remaining sustainable criteria are evaluated using Equations (4.9 - 4.14), where 4 No's of 8x8 matrices for 58 respondents are performed. The average of individual priority weight is evaluated, using arithmetic mean operation and are represented in Figs 4.7 & 4.8.

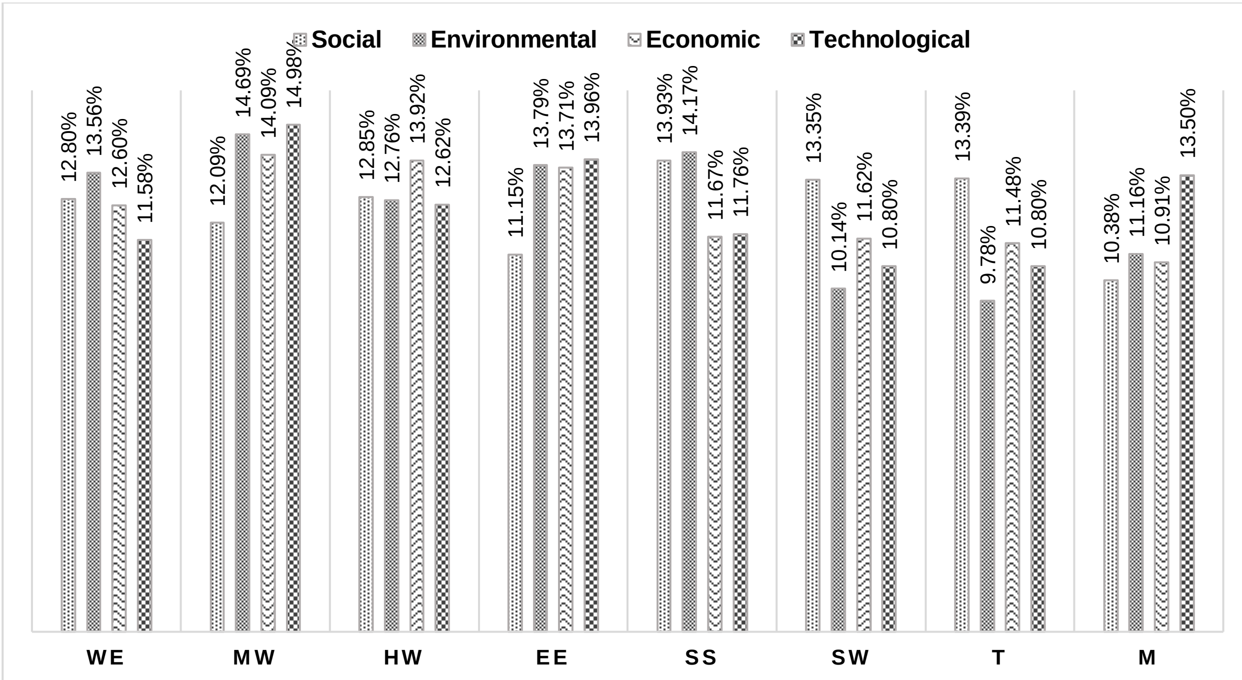


Fig. 4.7 Relative weights for sustainable criteria w.r.t sustainable SEET indicator

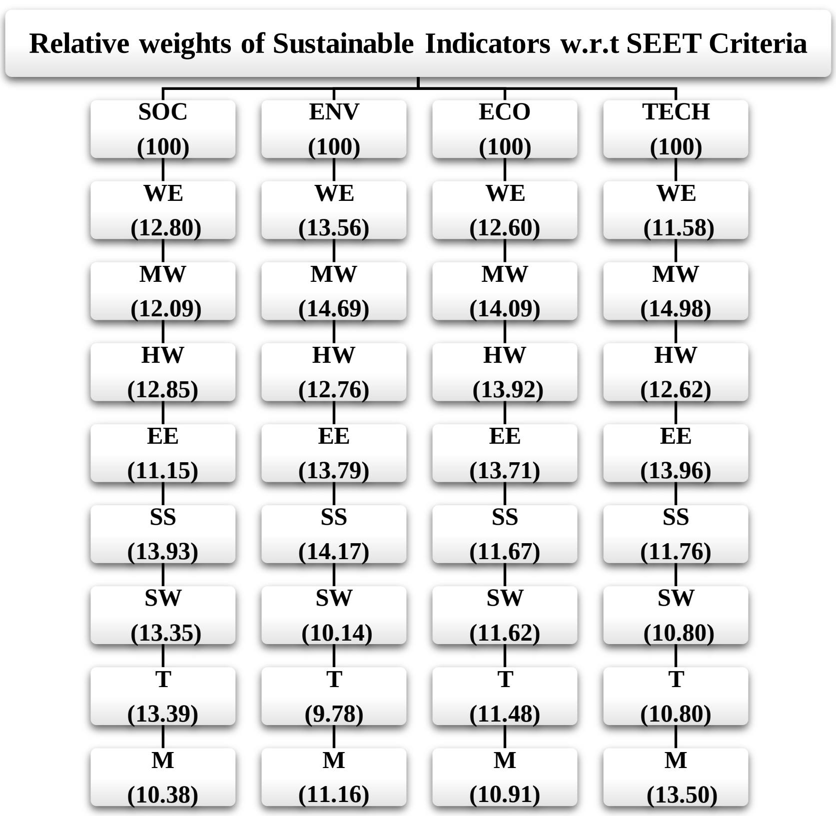


Fig. 4.8 Relative weights for Sustainable Criteria for each sustainable Indicators

Step 6: Similarly, the steps (4.4 to 4.8) are performed to obtain the relative weights of indicators (SEET) w.r.t criteria, where 8 No's of 4x4 matrices for 58 respondents are performed and the final weights are obtained as shown in Fig (4.9 & 4.10).

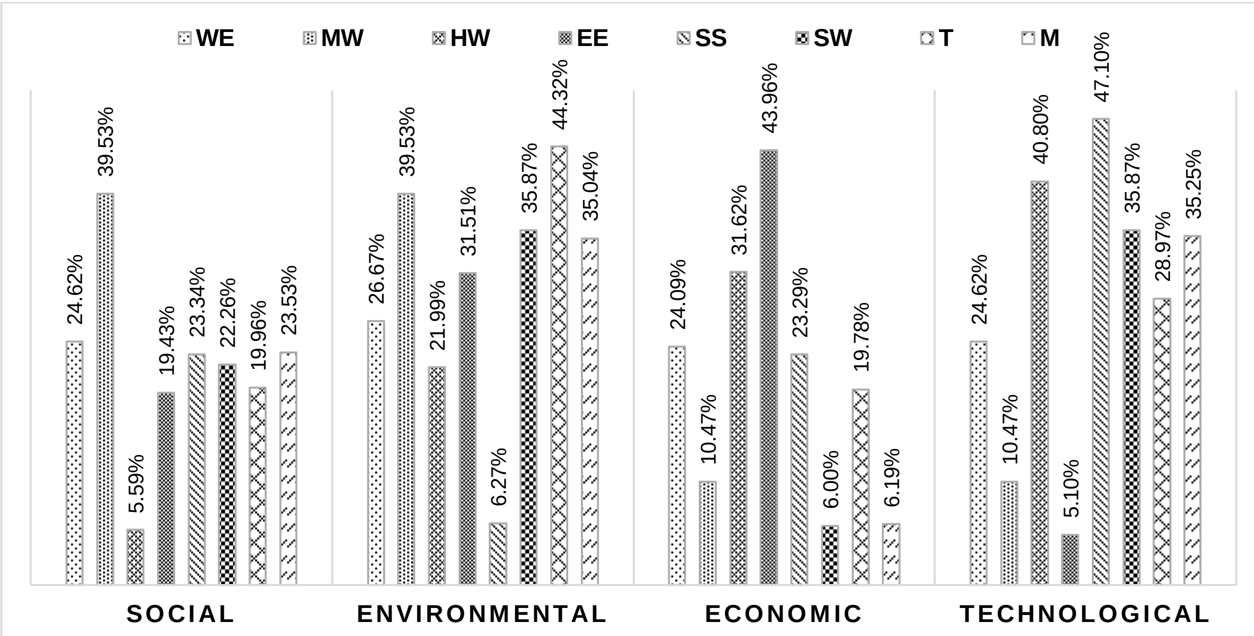


Fig. 4.9 Relative weights for sustainable Indicators w.r.t sustainable Criteria

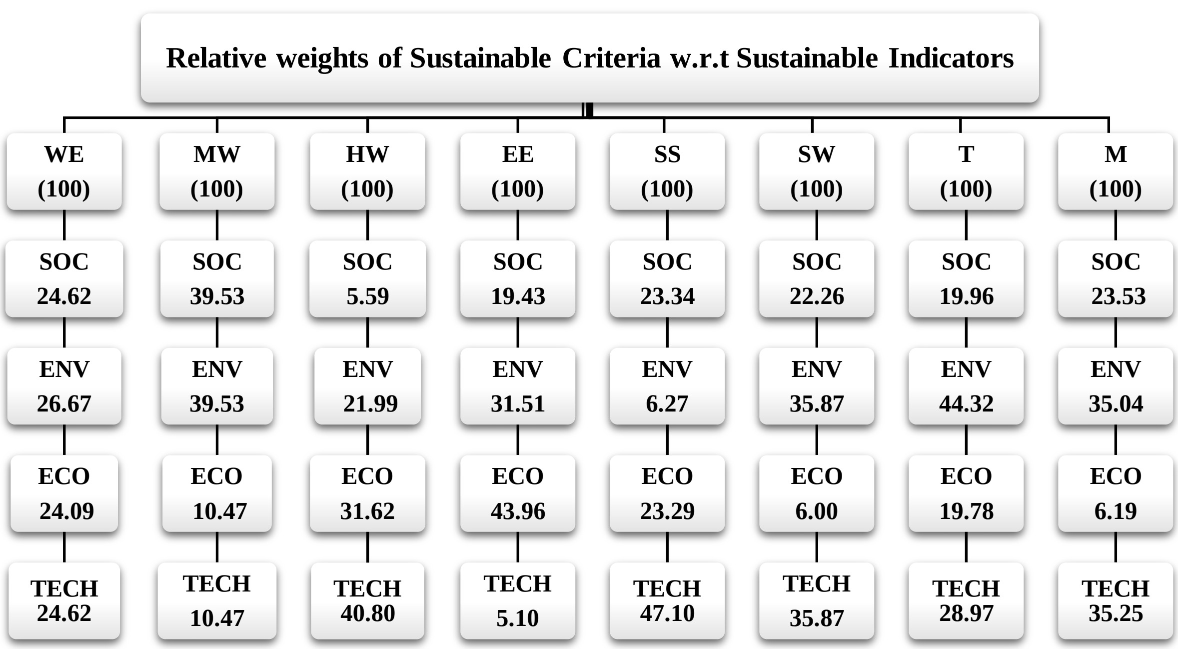


Fig. 4.10 Relative weights for sustainable Indicators for each sustainable Criteria

Step 7: The interrelated weights are obtained by multiplying the relative weights of sustainable indicators and criteria (Fig 4.11).

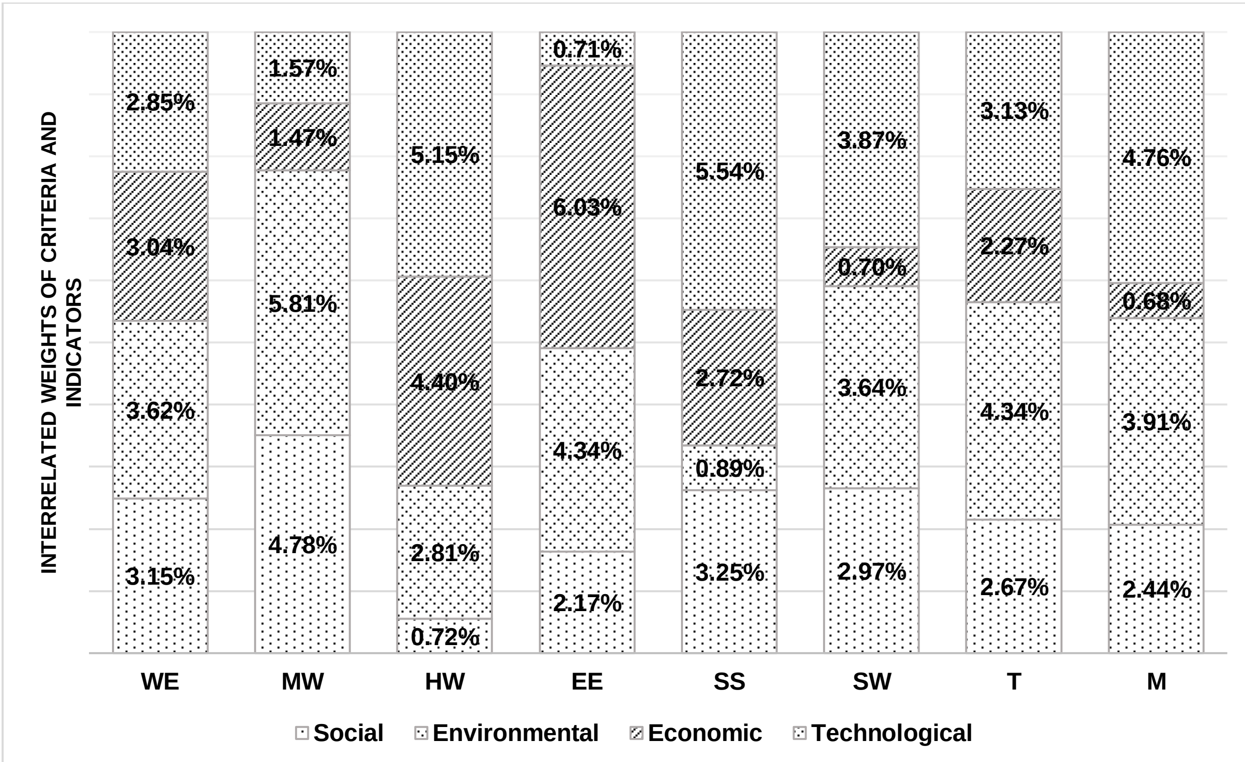


Fig. 4.11 The interrelated weights for SEET indicator w.r.t sustainable criteria

From Fig 4.9, considering Social indicator, the criteria Sustainable Sites (SS) has attained the highest weight (i.e.,13.93%) among the Eight criteria and overall rank sixth among 32 criteria (say 8 criteria x 4 indicators). Following it, the criteria, Transportation (T) and Social Welfare (SW) have achieved weights of 13.39% and 13.35% with an overall ranking of 12 and 13 respectively.

Considering Environmental indicator, the criteria Materials and Waste Management (MW) has attained the highest weight (i.e., 14.69%) among the eight criteria and overall rank second among 32 criteria. Following this, the criteria Sustainable Sites (SS) and Energy Efficiency (EE) has achieved a weight of 14.17% and 13.76% with an overall ranking of Eighth and Third respectively.

Considering Economic indicator, the criteria MW has attained the highest weight (i.e., 14.09%) among eight criteria and an overall rank of fourth among 32 criteria. Next, to it, Health and well-being (HW) and Energy Efficiency (EE) has achieved a weight of 13.92% and 13.71% with an overall ranking of seventh and ninth respectively.

Similarly, in Technological indicator, MW and EE have attained highest weight (i.e., 14.98% and 13.96%) and ranked first and fifth among 32 criteria respectively.

Based on Fig 4.10, it can be observed that the criteria MW has a major role in creating social justice to the built environment. It also reveals that with the use of efficient, non-pollutant and eco-friendly vehicles, there will be a reduction in the emissions and pollutants, further leading to reduced environmental impacts. Similarly, it can be noticed that the use of EE materials and technologies will benefit the user over a period of time. However, the initial cost may be high, but, the cost to benefit ratio would be very low, due to a reduction in operational and maintenance cost. With proper implementation of guidelines and policies with respect to sustainable design principles of the buildings (technological indicator), the criteria, SS, eventually provides the source to attain the allotted weight. From Fig 4.11, it can be noticed that for assessing the performance of a building towards sustainability, the criteria EE has highest interrelationship weight (6.03%) corresponding to Economic indicator, Secondly, MW corresponding to Environmental indicator has a higher weight (5.81%). Similarly, SS in Technological indicator (5.54%), MW in Social (4.78%) and Management (M) in Technological (4.76%) indicator. Considering the interrelated weights of criteria and indicators, the average weights obtained by pooling along the criteria w.r.t Social, Environmental, Economic and Technological indicators (i.e., 2.77%, 3.67%, 2.66% and 3.45%) is taken as a cut off value to observe the effective or most significant criteria responsible for indicator performance. The weights which are higher than the obtained average weights are highlighted in Table 4.16. Then, the normalized % weights are calculated for criteria and indicators. It is noteworthy to observe that the Technological indicator incorporated along with Triple-Bottom line (Environmental, Social and Economic) has the highest weight (28.4%) among SEET indicators. Similarly, Sustainable sites (SS) and Materials and Waste Management (MW) have achieved higher weights (16.91% and 15.56% respectively) among the Eight criteria.

Table 4.16 The interrelated weights of criteria and indicators

Criteria/ Indicators	Social (Avg>2.77%)	Environmental (Avg>3.67%)	Economic (Avg>2.66%)	Technological (Avg>3.45%)	Sum	Normalized %
WE	3.15%	X	3.04%	X	6.19%	**9.09%**
MW	4.78%	5.81%	X	X	10.59%	**15.56%**
HW	X	X	4.40%	5.15%	9.55%	**14.04%**
EE	X	4.34%	6.03%	X	10.37%	**15.24%**
SS	3.25%	X	2.72%	5.54%	9.51%	**14.91%**
SW	2.97%	X	X	3.87%	6.85%	**10.06%**
T	X	4.34%	X	X	4.34%	**6.37%**
M	X	3.91%	X	4.76%	8.67%	**12.74%**
Sum	14.15%	18.40%	16.18%	19.32%	**68.06%**	
Normalized %	**20.8%**	**27.0%**	**23.8%**	**28.4%**		

5.0 Summary of Phase – I study

This phase of study is aimed at incorporating local context, regional variation, climatic conditions, and topographical aspects by crucially observing a number of criteria and sub-criteria to reflect and diagnose regional sustainability in India. The study has refined and tailored the indicators, criteria and attributes to adopt to the Indian context. The findings reveal the significant indicators with respect to criteria considering climate variations, local context, topographical, culture and heritage. It was observed that among the perceptions of various experts, designers felt the importance of incorporating sustainable principles at the initial design stages to achieve sustainable construction. The Academicians and Architects were more concerned about the shift of conventional construction to sustainable construction, scope and future of the construction industry for achieving sustainability. From the findings, it can be stated that the criteria, Energy Efficient (EE) and Materials and Waste Management (WM) highlights the concept of Reduce, Recycle and Reuse (3R's) during the life cycle of building. This ultimately reflects the present scenario of development strategies in India discussed in Section 4.1.

The following are the specific conclusions derived from the first phase of study:

- There is an imperative need for encouraging and adopting sustainability principles in developing countries like India. The study found that the development of the nation involved with adoption of sustainable principles in construction industry promotes overall growth without disturbing the eco-system and avoiding adverse impacts caused by the conventional principles and practices in India.

- The study brought out the significance of the proposed ‘Technological’ indicator and encouraged Quadra-Bottom Line approach in implementing and achieving sustainable construction. This facilitates incorporation of innovative ideas and implement the concepts of Reduce, Recycle and Reuse (3R’s) into design principles.
- Based on the comparison of LEED, BREEAM, IGBC and GRIHA assessment tools and guidelines undertaken in the study, relevant criteria and their related attributes for assessing the performance of a building are identified. For this, the study utilized the Delphi Technique (DT) and Relative Importance Index (RII) in finalizing the attributes, criteria, and indicators.
- Based on DT and RII, the present study defines 37 attributes broadly under eight major criteria that are most appropriate for assessment of the sustainable performance of criteria for construction in India. These criteria include Water Efficiency, Materials and Waste Management, Health and Well-being, Energy Efficiency, Sustainable Sites, Social Welfare, Transportation, and Management. These criteria facilitate policymaking, guidelines, and development of the green building rating tool.
- The study also proposed a conversion scale from Likert scale (1 to 7) to Saaty scale (1 to 9) to avoid the complexity while performing the pairwise comparison. This enabled in receiving a good number of respondents in less time.
- The use of Fuzzy set theory facilitated to eliminate the uncertainty and ambiguity of human judgment. The relative weights are calculated using Analytical Hierarchy Process, a subjective pairwise comparison.
- Among SEET indicators, Environmental indicator has secured the highest weight of 30.15% and Technological indicator is next to this, with a weight of 28.52%.
- Among all the criteria, Materials and Waste management (MW) has attained the highest relative weight of 13.96% and subsequently, Energy Efficiency (EE) attained 13.15%. The MW secured the first position and EE is ranked fifth among 8 criteria. It is noteworthy to observe that both these criteria belong to Technological indicator.
- The normalized interrelated weight of Technological indicator has attained highest weight of 28.40% prior to Environmental indicator of 27.01%. This clearly highlights the

importance of integration of Technological indicator with a triple-bottom-line approach to form quadra-bottom-line approach in achieving sustainable construction.

- Based on the interrelated weights, the criteria WE, MW, SS, and S are categorized under Social indicator, MW, EE, T, and M are categorized under Environmental aspect. While, WE, HW, EE, and SS are grouped under Economic indicator and HW, SS, SW and M criteria are categorized under the Technological indicator.

It can hence be concluded that the Materials and Waste Management criteria has significant importance in assessing the building performance. Also, along with Social, Environmental Economic indicator, and Technological indicator is needed for achieving a sustainable construction.

Chapter 5 deals with the quantification of the eight criteria identified in the present Chapter using suitable attributes, pre-requisites, and evaluation standards keeping in mind developing countries like India.

CHAPTER - 5

QUANTITATIVE ASSESSMENT OF SUSTAINABLE CRITERIA TO ASSESS BUILDING PERFORMANCE

Phase II

Objective: To evaluate the building performance through quantitative assessment of sustainable criteria by establishing relevant quantifiable attributes and pre-requisites for appraisal.

5.0 Introduction

Chapter 4 dealt with identification, comparison and evaluation of relative weights of criteria and indicator and establish inter-relationship between them. The present chapter focusses on performance of a sustainable building based on the quantification of associated attributes and prerequisites for criteria. In developing countries like India, rapid population growth lead to urbanization and infrastructure development. By the year 2050, the population is estimated to increase by 50% and will gear up the requirement for material resources, water, and energy (Berardi, 2015; Reddy et al. 2019). It is also predicted that energy consumption will increase by seven times in residential buildings by the year 2032 (Franco et al. 2017). In addition to the consumption of resources, the release of CO_2 emissions and waste will affect the environment leading to ecological imbalance. It is observed that globally buildings consume 40% of energy, 42% of water, and 50% of resource by emitting 50% of air pollution, 51% of water pollution and 42% of greenhouse gases (Akizu-gardoki et al. 2018). Therefore, the construction sector has a significant impact on carbon footprint and energy consumption. The heavy requirement of fossil fuels will diminish the non-renewable resources producing large amounts of emissions and waste. Keeping in view this alarming trends, it is required to implement sustainability principles by providing passive design requirements, improving the efficiency of materials, streamlining the regulations, and modifying the guidelines to execute and monitor old and new residential buildings. This facilitates to assess the environmental burdens caused by the buildings. The challenge of the construction sector is not only to protect the environment but also benefit socially, and improve the economic feasibility (Rageh, Hosny & Abdel-Rehem, 2017).

5.1 Challenges and opportunities

With economic development of India rapidly growing, there is population and urbanization. Economic growth improves the living standards of the people, but this eventually increases the consumption of resources and energy, leading to the ecological crisis (Reddy et al. 2018). In developing countries like India, the immense challenge of reducing emissions and waste is getting worse due to the impacts of construction industry (Bhatt & Macwan, 2012).

Considering common concerns and specific priorities of developing countries like India, the study has recognized and explored eight criteria and four indicators for assessing the sustainable building performance and further made a scope to extend and quantify the identified criteria based on the attributes and prerequisites. In the previous chapter, relative weights of sustainable criteria and indicators (SEET) were determined to evaluate the interrelationship between sustainable criteria and indicators using the concepts of fuzzy logic and MCDM i.e., Fuzzy Analytical Hierarchy Process (FAHP). The degree of relationship of each criterion corresponding to SEET indicators is observed to evaluate the preference-based sustainable performance of the building. The present chapter deals with the quantitative assessment of these eight criteria by establishing relevant attributes and pre-requisites. Based on the existing assessment tools, guidelines & policies and field practices, the pre-requisites are recognized keeping in view the regional content, culture, heritage, topographic features, and level of public awareness in India, to assess the attribute performance.

The present chapter highlights assessment of the degree of performance of a sustainable building based on the quantification of associated attributes and prerequisites through three steps: Collection of data samples, determining relative weights and assessing the attribute performance. For each criterion, a set of attributes are determined covering various aspects related to design, construction and operation of a building. Each attribute is assigned with a quantifiable weight and a set of performance benchmarks that are largely quantifiable and assessable. First, the data has been collected from eight focused expertise groups comprising of Academicians, Consultants, Contractors, Designers, Engineers, Architects, Suppliers and Other stakeholders of the construction industry based on a structured questionnaire on a Likert scale of 1 to 5. The concept of

FAHP was adopted to determine the relative weight of attributes, as described in section 4.11.

5.2 Building Assessment Tool in India

The assessment methods depends on the selection of criteria and the suitability of criteria, affects the transfer of applicability of available environment assessment tools to different nations (Alyami et al., 2015). The main factors include site conditions, specific climate, geography, resource consumption and level of public awareness. India exhibits a wide range of climates, cultures and topographical features. Understanding the sustainability features will change with respect to the criteria. In such cases, it is not possible to incorporate the existing tools like Leadership in Energy and Environment Design (LEED) to assess the building performance. The rating system, Green Rating for Integrated Habitat Assessment (GRIHA), an indigenous building assessment tool basically assesses the no-air and air-conditioned buildings. It mainly stresses on the energy efficiency and thermal comfort caused by passive design techniques. It consists of 37 attributes under eight criteria to assess the institutional, industrial, and residential buildings.

According to Association for Development and Research of Sustainable Habitant (ADaRSH), a GRIHA Secretariat it is suggested that some of the criteria like tree preservation, material efficiency and replacement levels considered in the GRIHA are not fully applicable to all the locations or regions in India. Rana & Bhatt, (2016) stated that due to climatic, geographic and topographical conditions, the GRIHA rating suitable to one region is not suitable to other region. Similarly, Reddy et al. (2018) and Vyas & Jha, (2016), have developed a building assessment tool based on Multi-Criterion Decision Making (MCDM) method using the perception of various stakeholders of construction industry involved with some common criteria. Both LEED and GRIHA assessment systems have failed to cover the relative importance of criteria. The building assessment will be in a nascent stage by the year 2025 with incorporation in building codes and standards (Vestian Report, 2016). The initiative of the Government of India like smart city has a positive impact on sustainable building growth considering sustainable construction practices and smart technologies. There is a need to develop a new comprehensive and simple tool for assessing the sustainable building performance inevitably, to monitor and execute the pre and post construction of buildings. The present study focuses on developing a new green building rating tool (Sustainable Building Assessment Tool) considering relative weights for a broad range of criteria and their associated attributes. It is important to develop a scoring system for the Sustainable Building Assessment Tool (SBAT), to quantitatively analyze the building performance using well-defined criteria (8) and attributes (37).

5.3 Sustainable criteria and their related attributes

The present work identified eight criteria and 37 attributes which are prominent and suitable for the Indian context for assessing the sustainable performance of infrastructure. The following sections explain the importance of each criterion considered for evaluating the building performance.

5.3.1 Water Efficiency

The Earth's surface is covered up with water by 71.7%, yet just 3% of this water can be utilized as consumable water. Water is essential for the sustenance of human life. It has become a crucial commodity in our daily life. With the rapid growth in population, water preservation has turned into a noteworthy issue. Green buildings are increasingly becoming popular world over, to limit the utilization of assets, decrease different harmful impacts on the environment and make a perfect ecology. With the increasing need for water, water preservation has become the primary criteria for a sustainable building.

Conservation of water is the fundamental standards of any green structure. The actions are required to assure that the material and technologies that are utilized should help in decreasing the water utilization in building and landscaping areas. The principle of sustainability believes in making use of alternative sources of water to meet the demand by improved technologies and practices that deliver reduced water consumption. For example, taps, toilets, showerheads, urinals and so on, ought to be water efficient. Sustainable buildings prevent water pollution, make use of recycled treated water, conserve water and reduce water consumption. In the present study, the water efficiency criteria have been assessed based on the following five attributes.

5.3.1.1 Water monitoring and leak detection

The communities and residents have no alternative to the source of water, unlike electricity. By the installation of water meters, it is possible to reduce water wastage. The water monitoring meter/sub-meter is attached to the water main in order to observe and measure the general usage in daily-wise activities. It enables to track the water bill for over

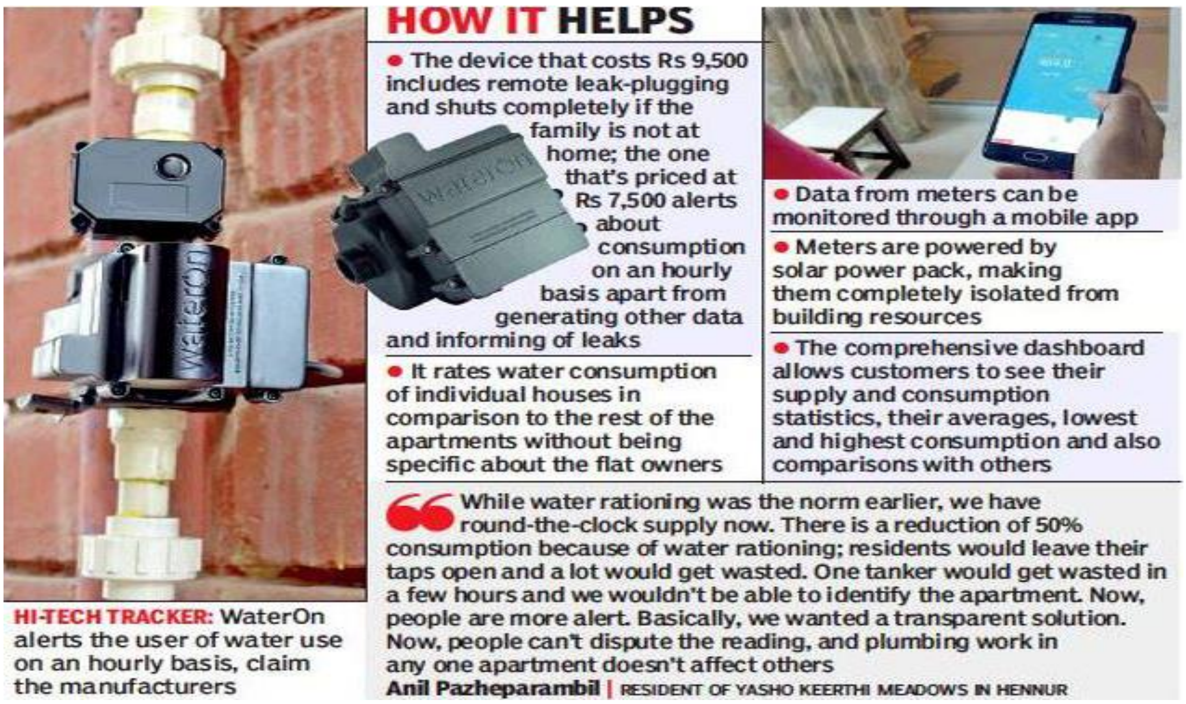


Fig. 5.1 Water meters

(**Source:** Times of India 15th Jan 2018)

and under usage. Also, other water saving measures like water leakages can also be detected by installing the monitoring systems. The water meters allow users to see their supply and consumption statistics, averages, lowest and highest consumption and comparison with others. The water meters measure, monitor and control the water usage (Fig. 5.1).

5.3.1.2 Building water use reduction

Use of efficient plumbing fixtures, sensors, auto control valves and pressure reducing devices can result in a significant reduction in water consumption in a building. Use of low flow plumbing fixtures promotes less water usage in the building. These are applicable to faucets, water closets, kitchen sinks, urinals, aerators, toilets, and showerheads, etc.,

5.3.1.3 Recycle and Reuse of water

Water scarcity, poor water quality, and water-related disasters are the major concerns related to current and future water resources. To meet the ever-growing water demand, there is incessant sourcing of groundwater without any replenishment leading to severe groundwater depletion adding further to the water stress. For this reason, water is brought to urban areas from very far-off places at a high cost to the urban centers. It can be observed from Fig. 5.2 that, there is an increasing trend of declination in the per capita water availability over the years. Keeping this in view, there is a need to recycle and reuse the water at the site and treat the wastewater generated at the source itself instead of conveying the same to far off places before final disposal.

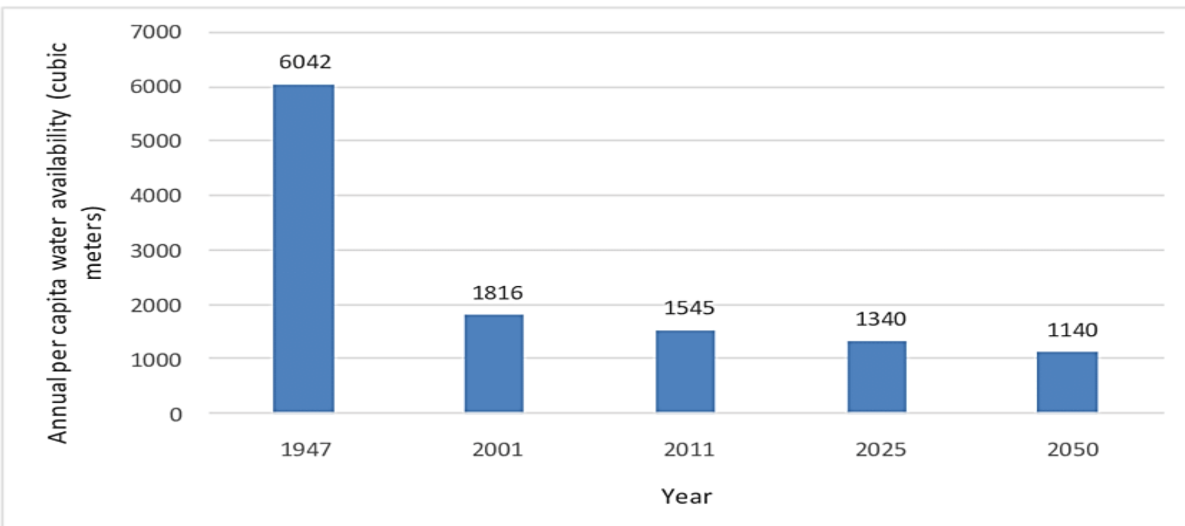


Fig 5.2 Reduction in per capita water availability

(**Source:** GRIHA manual V5, 2005)

5.3.1.4 Rainwater Management

The process of inducing, gathering, storing and conserving surface runoff water for recharging the groundwater is said to be rainwater management. Making optimum use of rainwater at the place where it falls, is of paramount importance. The rainwater can be harvested from rooftops, paved and unpaved areas including infiltration or collection features, stormwater drains and by increasing the permeable lot area, all these ultimately reduce the urban flooding.

5.3.1.5 Reduction in Landscape water requirement

The manner in which the landscape is maintained shows an incredible impact on water use. The water-efficient landscape design, installation, management, and maintenance can effectively reduce water demand. The innovative water harvesting method, an alternative water supply for landscape will reduce the water usage. Also, the reclaimed water can be used for gardening and replenishing surface water and groundwater.

5.3.2 Materials and Waste Management

The construction sector in India is growing at a fast pace, resulting in the demand for construction materials. Materials play a vital role in reducing the overall embodied energy of the building, thereby reducing the operational cost in its whole life cycle. The Life cycle Inventory (LCI) of the building materials are to be developed in terms of energy requirement, carbon emissions and waste generation throughout its life cycle. Developing countries like India are utilizing the developed countries LCI database in interpreting the energy requirement and emissions. Developing the LCI data is a time-consuming process and involves various stakeholders to provide data in various stages of the material life cycle. Thus, there is a need to identify alternatives to conventional building materials to have minimal impact on the environment. Most of the building materials used during construction are environmentally harmful if they are not properly handled. Some materials are harmful during handling and some during disposal. Similarly, every construction project generates waste if proper waste management strategies are not followed. The causes for waste generation could be the over consumption of resources, material damage, design failure, rework excess material preparation and demolished waste, etc. In the present study, the material and waste management criteria are being assessed based on the following five attributes.

5.3.2.1 Low Energy Materials

The challenge for the designers is to select a material with low energy, cost-effective and is environmentally responsible. Materials used for manufacturing the products should be renewable, cause a low impact on the environment, and pollute less, and reduce damage to the ecosystem. Some of the materials with low energy are salvaged timber, bamboo plywood, rubber, jute stalk boards, veneered panels, particle boards, natural fibers, resins, glass, gypsum, cement plaster boards, recycled material glass, crushed stone, terrazzo tiles, ceiling tiles, concrete flooring, industrial by-products, recycled aggregates and other wastes.

5.3.2.2 Regionally available materials

The over-exploitation of conventional resources results in depletion of non-renewable resources, the release of pollutants, deteriorating urban environment, disturbs the ecosystem. The major burden in procuring the materials is the source of manufacturing units. In most of the building materials, the cost to transport materials is higher than the cost of material, at the same time the transportation stage emits huge pollutants. The purpose of opting regionally available materials is to curtail the energy consumption in the transportation stage and encourage utilization of renewable materials. The use of waste filler materials obtained from construction and demolition waste could be one of the options to regionally available materials. Similarly, the use of by-products from industries like flyash, slag, quarry dust, ash in concrete will not only reduce the landfill but also reduce the overall weight of the structural component and enhance the concrete performance at optimum dosage.

5.3.2.3 Recycle and reuse of materials

Manufacturing a new product/material requires a lot of raw materials and energy. Instead of using virgin materials, use of recycled materials with low energy will reduce the environmental burden and conserve the non-renewable resources. The use of recycled materials not only reduces waste but also prevents pollution and landfills. Materials with high reclaimable capacity will sustain greater number of iterations until its reusable life.

5.3.2.4 Responsible sourcing

The commitment to sustainability can be demonstrated through responsible sourcing. It is beyond what we think about quality, cost and time. Responsible sourcing of materials stabilizes the environmental, social, and economic aspects. This attribute encourages the need for life cycle assessment of materials responsible for managing the resources.

5.3.2.5 Efficient Waste Management

For sustainable management of resources, reduce, recycle, and reuse waste is identified for better organization. It is an important aspect of sustainable building. Effective strategies will reduce the waste during construction, waste segregation, disposal, and public awareness of disposal issues.

5.3.3 Health and Well-being

Environmental health and well-being are interdependent. The sustainable building promotes long term health and mental well-being of an individual. It focuses on the quality of life and increased livelihood. Sustainable buildings maximize productivity and attain good health. The occupant comfort can be enhanced through better indoor air quality, proper sanitation, humidity, and low temperature. The following attributes will assess the health and well-being of occupants in the building.

5.3.3.1 Water Quality

Water is essential for socio-economic development and a healthy ecosystem. It acts as a link between human society, climate, and ecosystem. The United Nations (UN) Sustainable Development Goals (SDG) has recognized the importance of water in sixth goal. This is related to water ecosystem which includes rivers, wetlands, aquifers, and lakes for sustaining biodiversity. The UN-Water's overarching goal is "Securing Sustainable Water for All". By encouraging water governance, sustainable sanitation, wastewater treatment, improved drinking water sources create healthy eco-system. There is a growing need for fresh and hygienic water which is functionally intact and biologically complex. According to UN SDG's, fresh water plays a vital role in sustainable development like food and energy production aspects (Allen et al., 2017). It is important to monitor quality assurance of water for drinking purpose to support the scientific assessment.

5.3.3.2 Outdoor and indoor noise levels

The quality of life in urban areas is affected by high noise levels. The outdoor noise levels are impacted by traffic volume and congestion. Similarly, indoor noise is caused by human activities, machines, and music. These noise levels beyond the limits create hearing problems, increases blood pressure, sleeplessness, irritability, and stress. The noise from outdoor traffic and indoor human activities will affect the building environment and impact the health of human. For better health and well-being, the outdoor and indoor noise levels are to be within the permissible limit of 65dB.

5.3.3.3 Sanitation/Safety facilities and accessibility

To ensure safety of public health and environment, the garbage generated from household, industries and other facilities should be properly disposed of. Improper dumping of garbage generates more clogging, blocking and producing mosquitoes and illness to health. Further, to avoid clogging of roads and pipes, garbage should be collected, stored and disposed of properly. For this, proper garbage disposal system has to be implemented by local authorities.

5.3.3.4 Minimize ozone depletion (CFC -based refrigerants)

Chlorofluorocarbons (CFC) and Hydrochlorofluorocarbons (HCFC) are mostly used for propellants, solvents, air conditioners, and refrigerators, which contain chlorine that destroys the ozone layer. It is important to reduce and further eliminate the CFC's and HCFC's producing appliances. The appliances to be utilized should be approved by the Bureau of Energy Efficiency (BEE) to promote energy efficiency and eliminate CFC emissions.

5.3.4 Energy Efficiency

Due to rapid population growth, there arises an increasing energy demand and carbon footprint. Renewable energy resource is the key source to meet the present demand. Energy efficiency relates to the conservation of energy by utilizing less amount of energy to provide products and services. This includes installation of energy efficient appliances to serve the purpose, by consuming less amount of energy, which in turn reduces the operation and maintenance cost. Moreover, with the use of energy efficient appliances, there are multiple benefits which include mitigating climate change, reduction in pollution, reduced cost and better indoor conditions. The following significant attributes will enable assess the energy efficiency parameter.

5.3.4.1 Renewable energy production

The energy which is naturally replenished from sunlight, wind, hydro, geothermal and biofuel is said to be renewable energy. It is highly recommended to generate and install renewable energy systems wherever necessary, to meet the high demand. Installing solar panels for energy generation has to be given major importance in meeting the household demands. This will reduce the overall burden on fossil fuel consumption and the environment.

5.3.4.2 Energy efficient appliances

The appliances which consume less energy during their service life and save on energy expenses are treated to be energy efficient. Higher the consumption of energy, greater will be resource exploitation. This exploitation of natural resources can be reduced by utilizing energy efficient appliances. The use of these kinds of appliances significantly lower greenhouse gas emissions. The appliances with Bureau of Energy Efficiency (BEE) labeling recognized by Ministry of Power, Government of India are recommended for installation.

5.3.4.3 Energy monitoring

Energy monitoring supports the energy efficiency in real-time monitoring and controlling helping in reducing the energy consumption associated with household appliances. This strategy facilitates to curtail the energy usage and amount of money spent on it. The use of sub-meters enables to manage the measure of consumption of electricity.

5.3.4.4 Reduction in energy consumption associated with interior lighting

Emphasis on daylighting utilization will reduce the energy consumption associated with interior lighting. The open spaces in and around the building will cater to essential daylight and ventilation. The code of practice IS 3646 (Part 1): 1992 suggests the general requirements for interior lighting (IS 3646:1992). The light Power Density (LPD) is the measure of energy saving for space. It is the watts of lighting per square foot or square meter of floor area. The maximum lighting power density is 0.48 W/sq.ft or 5.2 W/sq.m. Based on the percentage reduction of LPD, the reduction of energy consumption associated with interior lighting can be measured.

5.3.4.5 Adequate lighting

Sustainability provides a drive for making daylighting the primary light source in the building. The connection between exterior and interior environment depends on the adequate daylighting. Daylight factor is the indicator for good illuminance for space. It is the ratio of the internal light level to the external light level of a building. It provides minimum daylight standards in the room. Proper planning, layout, and orientation of a building can add adequate daylight illumination inside the building. Lighting depends upon the size and location of doors and windows, room size, and obstructions.

5.3.4.6 Energy efficient transportation systems

It is very essential to promote efficient use of vertical transportation technologies to save energy because the major portion of the cost lies with its operation and maintenance. The implementation of energy efficient solutions can manage and monitor the electricity consumption rate. All the transportation systems like elevators, escalators, etc., should be the Bureau of Energy Efficiency (BEE) certified (CPWD 2016).

5.3.5 Sustainable Sites

Sustainable site is a crucial factor for achieving the objectives of green building. With the increase in urbanization and environmental degradation, it has become imperative to protect, preserve and modify the surrounding environment.

5.3.5.1 Site Selection

Harmonizing buildings with the environment, social-economic aspects is an important component. Site selection addresses to maximize and conserve the land, water, flora and fauna, and natural habitat. The site should not consist of prime farmland and it should not be in flood hazard area.

5.3.5.2 Protect or restore habitat

To promote biodiversity, it is necessary to converse the natural areas and restore damaged areas. This minimizes the damage to the surrounding environment (habitat, species, water bodies, etc.,).

5.3.5.3 Heat island reduction

The urban area that is warmer than the surrounding rural area because of human activities causes heat island effect. The rise in temperature causes an increase in energy demand for cooling. These consequences can be avoided by increasing the shading of hardscapes around the building, installing rooftop garden insulators and providing non-absorptive material.

5.3.5.4 Open space

The sustainable performance of the building can be improved in terms of environment and social interaction, and physical activities. It can incorporate a pleasant view, peaceful, delightful and happy life. It makes the habitat to feel near to nature and environment.

5.3.5.5 Light pollution

The brightening of night sky in inhabitant areas, lighting where it is not intended to fall, causing visual discomfort or combinations of these thereof are some of the major issues of light pollution. This ultimately curbs the negative effects of light pollution on the surrounding environment. Proper design strategies can reduce the adverse effects of light pollution.

5.3.5.6 Conversation of soil surrounding the building

Preserving topsoil and avoiding erosion will protect the prime and unique farmland. The topsoil quality should meet with the quality standards of top preservation criteria as per NBC 2005 Part 10 (NBC 2005). The topsoil is fertile and properly laid for vegetative growth.

5.3.6 Social welfare

Sustainable buildings address the global problem of climate change, quality of living, health & well-being, and economic growth. The awareness towards sustainability makes the citizens motivate and implement sustainable principles. Better indoor air quality, water quality, and proper ventilation lead to improvements in the performance of sustainable building. The following are the attributes to assess social welfare criteria.

5.3.6.1 Awareness towards sustainable issues

The awareness is how knowledgeable someone is about the issues and practices. As it is very important to conserve and protect the natural environment and resources, the communities should consider and promote awareness. Improving awareness is also one of the aspects of strengthening sustainable development. Issues related to operation and maintenance in houses for appliances need to train. The importance of basic needs like energy, water, resources required to be addressed and awakened.

5.3.6.2 Efficient ventilation

Efficient ventilation is required to replace the indoor pollutants with fresh air and healthy indoors thus reduces the risk of human health issues. It is the most efficient way to cool the building and conserve energy. Efficient ventilation helps in reducing energy requirement and achieve good indoor air quality.

5.3.6.3 Design for durability

Durability is the key component of sustainable building. A long-lasting building can be easily judgeable about its durability design. The durability of a building depends on specific factors that can be addressed based on water absorption, acid attack, alkali, and alkaline content, thermal exposure, material functionality, fatigue, ductility, workmanship, etc.,

5.3.7 Transportation

The transportation sector is the largest air pollutant and greenhouse gas emitter. The sustainable mode of transportation has a low impact on the environment. This enables to find the most efficient way to connect our origins and destinations, that promote different modes of transportation, reduce congestion and create livable neighborhoods with sustainable designs. Sustainable transportation improves physical activity, social interaction, a healthier lifestyle, reduce environmental impacts and reduced cost. This includes walking, cycling, carpooling, car sharing, public transportation and use green vehicles. The following attributes facilitate in assessing the transportation criteria performance over a building.

5.3.7.1 Public transport accessibility

The automobiles are the major donors to environmental problems. The accessibility to the amenities should be nearby to reduce the use of automobiles. Better accessibility not only reduces the road congestions but also, improves the connectivity of people and location. Lack of public transport accessibility leads to social exclusion, an increase in land use. Therefore, public transport has crucial importance in attaining sustainable accessibility.

5.3.7.2 Use of bicycles by residents

Bicycles are non-pollutant and energy efficient. Cycling doesn’t cause any environmental damage. It promotes physical activity, good health, and reduced traffic congestions. It is the best alternative mode of transport for sustainable cities to travel to adjoining places.

5.3.7.3 Proximity to amenities

The automobile dependency reduces when the required amenities are nearby or at a walkable distance. The intention to encourage walking and cycling depends on the distance of amenities. If a number of amenities are nearby, then, the intention to use the automobile reduces.

5.3.7.4 Environmentally friendly pavements at the building site

Porous pavements permit water to seep and percolate through the ground. The use of non-porous materials eliminates the water drainage problem. The eco-friendly pavements increase the water table by avoiding floods and water clogging in drains.

5.3.7.5 Reduced parking footprint

Parking is the major source of air and water pollution, which is directly linked to the use of automobiles. Reduced parking minimizes the environmental impacts, consumption of land space and rainwater runoff. Alternative solutions are encouraged to reduce the parking footprint.

5.3.8 Management

Management and controlling is the major challenge in implementing sustainability principles in buildings. Managing balance between buildings and environment is subjective in nature. The fundamental requirements that can be recognized from environmental degradation could be waste disposal, preventing fire hazard, avoiding the use of polythene products, and promoting awareness about sustainable strategies.

Protecting habitat health by segregating, disposing or dumping common waste/garbage properly, preventing and controlling the damage causing from fire hazards, providing sustainable strategies in implementing the waste management will prevent the surrounding environment from degradation. Further, these will help in minimizing the effects of waste in poor communities for improving and achieving sustainability. The following attributes are considered in assessing the management criteria.

5.3.8.1 Managing balance between the building and its immediate surrounding

Waste management strategies enable able to manage the balance between building and surroundings. Various kinds of waste are produced from the construction, operation and maintenance stages of a building. It is important to manage the waste efficiently rather than dumping as a landfill. Reducing and preventing the waste generated from household activities and disposing of in a proper manner will help manage the balance between building and the surrounding. The waste generated during construction is disposed of in an inappropriate manner, resulting in hazardous or environmentally harmful practices disturbing the ecology. Proper handling and storage of construction waste, creating plan and space are equally crucial to waste management.

5.3.8.2 Managing fire prevention activities

It is important to protect the buildings from fire destruction. The basic requirement of fire protection will increase the integrity of the building. The implementation of fire protection strategies like fire protection systems, cavity barriers, and passive fire protection will facilitate in managing fire hazards. The loss of resources or materials invested in the construction of a building without considering fire risk strategies may result in uneconomical consequences. The fire protection systems like water sprinklers and sound alarms must be installed to provide prior warning in the event of a fire. The building fire design strategies should include the emergency exit, installation of fire hydrants, fire extinguishers, etc., to reduce the impact of fire damage and loss.

5.3.8.3 Preventing the reckless dumping of polythene products at the building site

The alarming threat that has been causing severe damage to eco-system is the use of polythene products like bottles, rubber, adhesives, lubricants, plastic bag, etc. This is the major reason for soil, water, air pollution, blocking of drainage pipes and sanitary pipes. The reckless dumping of polythene products near the building sites makes negative consequences for the environment mainly soil contamination. The general use of the plastic bag is the major source of environmental degradation; therefore, it should be completely prevented and avoided.

5.4 Methodological approach to quantify criteria

The present study is intended to refine and quantify the attributes considering various pre-requisites. The methodology of the study involves determining the relative weights of attributes and assign global weights to pre-requisites for developing a Sustainable Building scoring system. The hierarchy structure of various aspects (Indicators, Criteria and Attributes) at different levels is shown in Fig 5.3 for assessment of sustainability of a building. Based on the observation of the building from various aspects of sustainability, the pre-requisites pertaining to the attributes are identified. The attributes are weighed based on the possibility of quantification, using pre-requisites listed in Table 5.1.

5.4.1 Determining attribute weights

In order to assign relative weight to the attributes, a structured questionnaire survey is prepared in such a way that the importance of each of these attributes corresponding to their criterion can be assessed. The survey responses were focused on eight expertise groups including Academicians, Consultants, Contractors, Designers, Engineers, Architects, Suppliers and Other stakeholders of the construction industry. The total number of respondents involved in the questionnaire is 34 and the details are provided in Fig 5.4 (Appendix C).

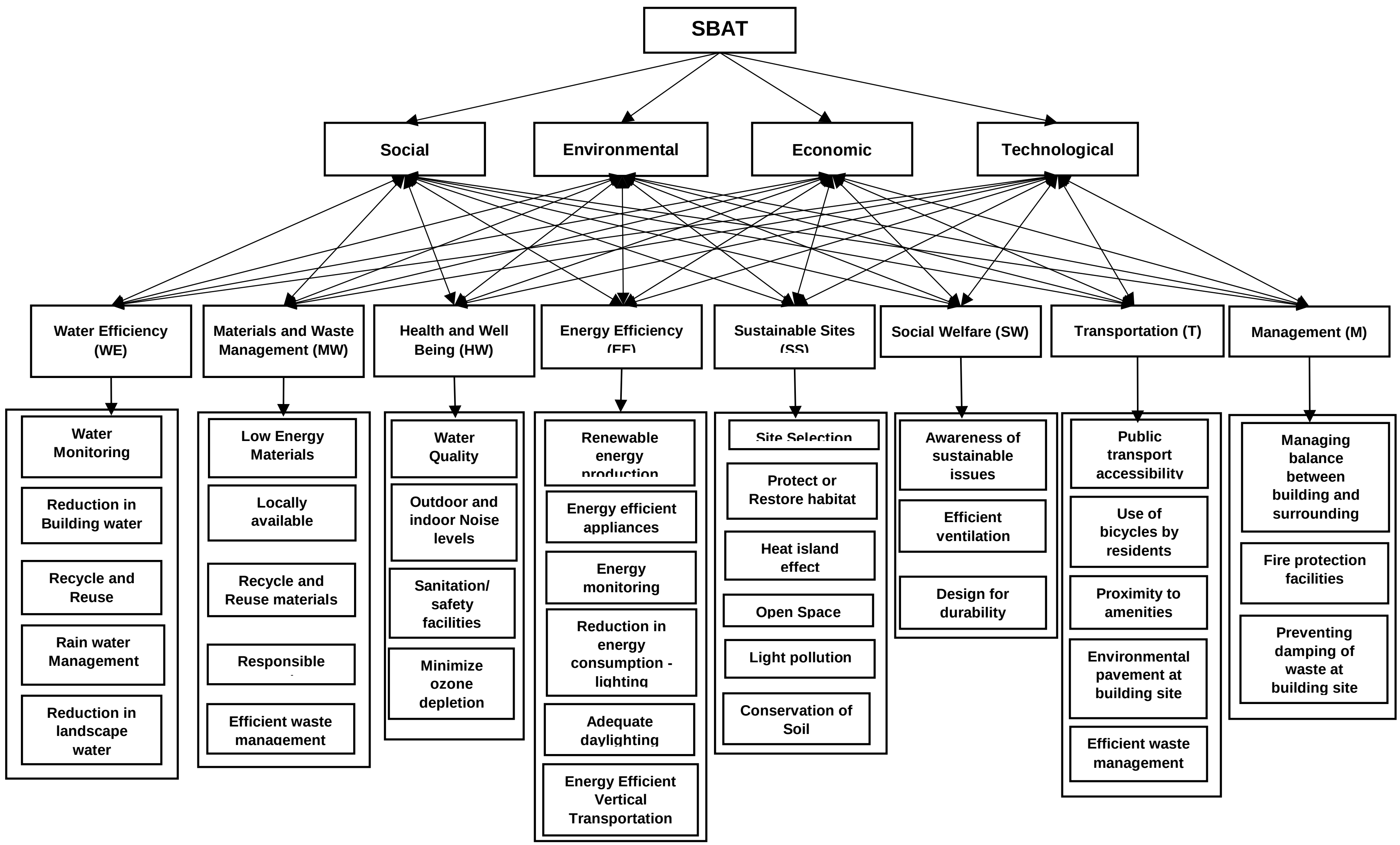


Fig. 5.3 Proposed Hierarchy Structure of Criteria, Attributes & Pre-requisites for developing Sustainable Building Assessment Tool (SBAT)

Table 5.1. Criteria weight, Attribute weight and Global weight to assess sustainable building performance

S.No	Assessment Criteria	Criteria Weight	Assessment of Attribute	Attribute Local weight	Allocated Credit Points - Global weight
1	Water Efficiency (WE)	12.63	Water monitoring and leak detection (A1)	22.52	2.84
			Building water use reduction (A2)	16.61	2.09
			Recycle and reuse of water (A3)	22.13	2.79
			Rainwater management (A4)	22.11	2.79
			Reduction in landscape water requirement (A5)	16.60	2.10
2	Materials and Waste Management (MW)	13.96	Low-energy materials (B1)	16.89	2.35
			Regionally available materials (B2)	21.56	3.01
			Recycled and re-use materials (B3)	20.52	2.86
			Responsible sourcing (B4)	19.69	2.74
			Efficient waste management (B5)	21.35	2.98
3	Health and Well-being (HW)	13.04	Water quality & water pollution (C1)	25.95	3.38
			Outdoor & indoor noise levels (C2)	24.13	3.14
			Sanitation/Safety facilities & Accessibility (C3)	26.35	3.43
			Minimize ozone depletion (C4)	24.57	3.07
4	Energy Efficiency (EE)	13.15	Renewable energy production (D1)	18.25	2.40
			Energy efficient appliances (D2)	17.57	2.31
			Energy monitoring (D3)	15.42	2.03
			Reduction in energy consumption associated with interior lighting (D4)	13.54	1.78
			Adequate daylight (D5)	18.14	2.39
			Energy efficient Vertical transportation systems (D6)	17.08	2.24
5	Sustainable Sites (SS)	11.21	Site selection (E1)	18.27	2.35
			Protect or restore habitat (E2)	17.30	2.22
			Heat island reduction (E3)	15.87	2.04
			Open space (E4)	14.70	1.89
			Light pollution (E5)	15.31	1.97
			Conservation of soil surrounding the building (E6)	18.55	2.38
6	Social Welfare (SW)	13.14	Awareness of sustainable issues (F1)	31.29	3.60
			Efficient ventilation (F2)	32.54	3.73
			Design for durability (F3)	36.17	4.15
7	Transportation (T)	11.36	Public transport accessibility (G1)	21.83	2.48
			Use of bicycles by the residents (G2)	21.10	2.39
			Proximity to amenities (G3)	19.13	2.16
			Environment-friendly pavements at the building site (G4)	21.89	2.36
			Reduced parking footprint (G5)	17.04	1.94
8	Management (M)	11.49	Managing the balance between the building and its immediate surrounding (H1)	32.76	3.75
			Managing fire prevention facilities (H2)	29.57	3.39
			Preventing the reckless dumping of polythene products at the building site (H3)	37.68	4.33
	Total				**100**

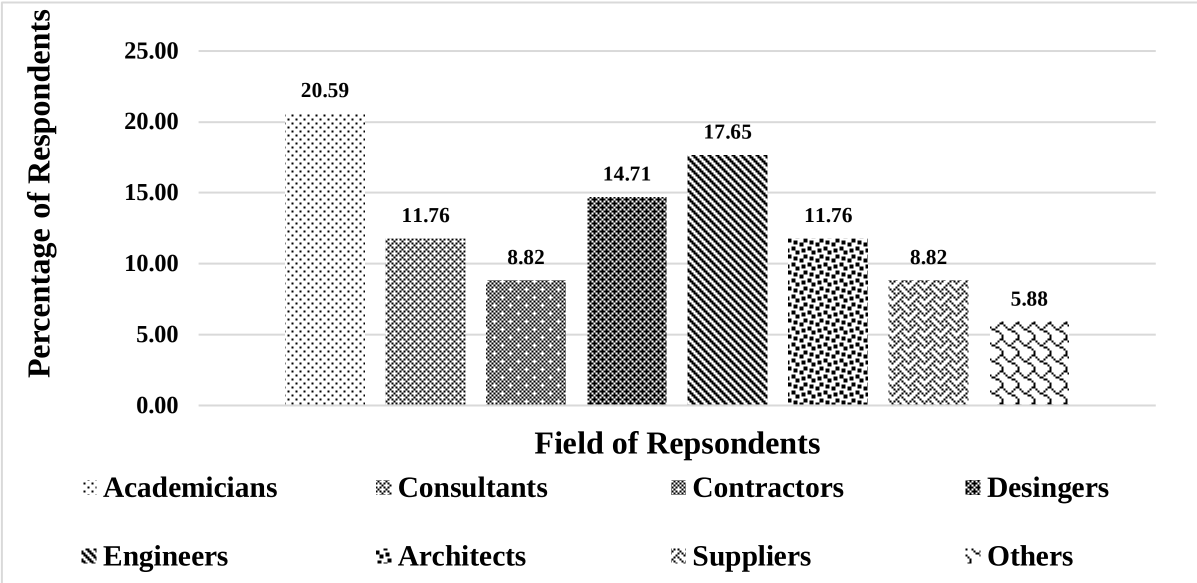


Fig. 5.4 Details of Respondents

The collected information from the questionnaire is further utilized for determining the relative weights of attributes.

Using FAHP, the relative weights of attributes are determined for developing a sustainable score in building assessment. The relative weight for the 37 Attributes are determined using the FAHP technique described in section 4.12, Chapter 4.

5.5 Results and Discussion

In order to make the tool easier to use, efforts are made to make the attributes quantifiable. The following are the details for quantifying the attributes based on the proposed pre-requisites and their credit points.

5.5.1 Quantifying Water Efficiency

1. *Water monitoring:* This parameter supports water efficiency efforts by monitoring and benchmarking water use over time. (*Credits to award* = 2.84)

Requirements: Water meter/sub-meter is fixed for each unit. Homes that use only well water and are not connected to a Government supplied municipal water system are exempted from this prerequisite.

2. *Reduction in building water use:* Intention is to reduce the demand for water through high-efficiency fixtures and efficient landscaping practices. An example of this

parameter based on water consumption and how the points are awarded is shown in Tables 5.2 and 5.3.

Table 5.2 Building water baseline consumption (per person per day)

Fixture	Estimated water usage (Litres)
Shower	58.4
The lavatory, kitchen faucet	41.5
Toilet	30.3
Clothes washer	57.1
Dishwasher	2.4
	Total = 189.7

Source: (U.S. Green Building Council. LEED v4, 2013)

Table 5.3 Points for reducing building water use

% Reduction in building water use	Normalized points	Points to award
10	0.1	0.20
10-15	0.2	0.41
15-20	0.3	0.62
20-25	0.4	0.83
25-30	0.5	1.04
30-35	0.6	1.25
35-40	0.7	1.46
40-45	0.8	1.67
45-50	0.9	1.88
Above 50	1	2.09

Source: (U.S. Green Building Council. LEED v4, 2016)

3. *Recycle and reuse of water:* The idea is to recycle and reuse water at the site and hence reduce the water demand. (Points to award = 2.79)

Requirements: Recycle at-least 50% of wastewater through mechanical/natural wastewater treatment systems.

4. *Rainwater management:* This parameter aims at reducing the rainwater runoff volume from the site.

Requirements: Use Low-Impact Development (LID) techniques like planting areas with native or adapted plant material, installing a vegetated roof, using permeable paving materials, and installing permanent infiltration or collection features, to minimize the amount of stormwater that leaves the site. To allocate the points, calculate the percentage of the lot area, including the area under a roof that is permeable or direct water to an on-site catchment or infiltration feature (Table 5.4).

Table 5.4 Points for the permeable area, as a percentage of total lot area

Percentage	Normalized points	Points to award
<50	0	0
50-64	0.33	0.92
65-79	0.67	1.84
>79	1	2.7928

Source: (U.S. Green Building Council. LEED v4, 2016)

5. *Reduction in landscape water requirement:* The intention is to reduce landscape water consumption. (Points to award = 2.10).

Requirements: Implement the following measures to reduce landscape water consumption, for the use of captured rainwater, use of reclaimed water, and use of water treated on site.

5.5.2 Quantifying Materials and Waste Management

1. *Low energy materials:* The intention of this parameter is to use low embodied energy products, hence reduce negative effects on the atmosphere. *(Points to award = 2.35)*

Requirements: Use salvaged timber, glass, gypsum board partitions, ceramic tiles, terrazzo flooring, crushed stone, recycled aggregate, and pozzolonas.

2. *Regionally available materials:* Intent of this parameter is to reduce the embodied energy of materials by using locally extracted, processed and manufactured products *(Points to award = 3.01)*.

Requirements: Products have to be extracted, processed and manufactured locally (Distance of influence =160Km) for the following components. Points have been distributed equally (1.00) for framing, Aggregate for concrete and foundation, and Drywall or interior sheathing

3. *Recycle and reuse materials:* Intention is to increase demand for products or building components that minimize material consumption through recycled and recyclable content, reclamation, and reduced life-cycle impacts. (*Points to award = 2.86*)

Requirements: At least 25% of reclaimed material has to be present in a product. Includes Salvaged, refurbished or reused materials (Example: Concrete: 30% fly-ash/slag in cement and 50% recycled content).

4. *Responsible sourcing:* Intention is to encourage the use of products and materials for which life cycle information is available and to encourage environmentally responsible forest management (*Points to award = 2.74*)

Requirements: Wood products must be Forest Stewardship Council (FSC) certified. (*Points to award = 1.3746*). Products should be from a manufacturer (producer) who participates in an extended producer responsibility program or certified with the competent authority (*Points to award = 1.37*)

5. *Efficient waste management:* Intention is to reduce waste generation and to carry efficient waste disposal (*Points to award = 2.98*)

Requirements: Points are equally distributed for the provision of multi-colored bins for waste segregation at source, provision of space for hygienic storage of segregated waste), and onsite efficient waste disposal or carried by the municipal community.

5.5.3 Quantifying Health and Well-being

1. *Water quality:* Intention is to ensure good quality of drinking water

Requirements: Drinking water should have the following qualities (Table 5.5). Total points to be awarded is 3.38.

Table 5.5 Water quality baseline data

Characteristic	Requirement	Normalized points	Points to award
Odour	Unobjectionable	0.142	0.48
Turbidity (NTU)	5-10	0.142	0.48
Ph	6.5-8.5	0.142	0.48
Total hardness	300-600 mg/l of $CaCO_3$	0.142	0.48
Fe	0.3 ppm	0.142	0.48
Cl	250-100 ppm	0.142	0.48
Free chlorine (residual)	0.2 ppm	0.142	0.48

(Source: Indian Standards for drinking (IS 10500-2003))

6. *Outdoor and indoor noise levels:* Intention is to ensure healthy noise levels (*Points to award = 3.14*)

Requirements: Points are distributed equally (0.62) for the following requirements

- The building should be at least 30 m away from a heavy traffic road (80-90dB)
- Wall or partitions should have a sound reduction index of 40 dB or higher.
- Earth berms and vegetation should be used to reduce noise levels (dense planting of trees).
- Doors and windows should be sound-proof.
- Appliances should be less sound making

2. *Sanitation/safety facilities and accessibility:* Intention is to assure sanitation/safety and accessibility at the building site (*Points to award = 3.43*)

Requirements: Points are distributed equally (0.68) for the following requirements

- Garbage should be collected without exposing to open environment.
- Wastewater should be disposed off properly.
- Steps should be taken to control mosquitoes.
- Disposal of the human excreta should be carried out in a systematic way in three steps of *separation, containment,* and *destruction.*
- Rubble should be disposed of quickly to avoid blockage of drainage, roads, etc.

3. Minimize ozone depletion (CFC-based refrigerants): Intention is to reduce the environmental degradation potential of the building (*Points to award = 3.07*)

Requirements: Points are distributed equally (1.02) for the following requirements

- All the insulation used in the building should be free from CFCs and HCFCs.
- All the HVAC and refrigeration equipment should be free from CFCs.
- Fire suppression systems and fire extinguishers installed in the building should be halon free.

5.5.4 Quantifying Energy Efficiency

1. *Renewable energy production:* The idea is to encourage the installation and operation of renewable electricity generation systems (*Points to award = 2.40*).

Requirements: A renewable electricity generation system should be installed to generate renewable energy at the site. The following points are used to allocate credit (Table 5.6)

Table 5.6 Points for the generation of renewable electricity

Annual production (kWh)	Normalized points	Points to award
500-999	0.1	0.60
1000-1499	0.3	1.20
1500-1999	0.6	1.80
2000 and above	1	2.40

(Source: U.S. Green Building Council. LEED v4, 2016)

2. *Energy efficient appliances:* Intention is to reduce energy consumption by ensuring that all the appliances operate at peak efficiency (*Points to award = 2.31*).

Requirements: Points are distributed equally (0.77) for the following requirements

- Refrigerators should be BEE (Bureau of Energy Efficiency) qualified.
- Ceiling fans should be BEE qualified.
- Other devices (washing machine, dishwasher, etc) should be BEE qualified.

3. *Energy monitoring:* Intention is to support energy efficiency efforts by monitoring and benchmarking energy use over time (*Points to award = 2.02*).

Requirements: An electricity meter or sub-meter for each residential unit must be installed.

4. *Reduction in energy consumption associated with interior lighting:* Intent is to reduce the energy consumption associated with interior lighting (*Points to award = 1.78*).

Requirements: Reduce the light power density by at least 35% over standard practices. The baseline for maximum lighting power density = 0.48 W/sq.ft or 5.2 W/sq.m and points are awarded according to Table 5.7

Table 5.7 Points for a reduction in light power density

Percentage reduction in light power density	Normalized points	Points to award
≥35 and <45	0.33	0.59
≥45 and <55	0.67	1.18
≥55	1	1.78

(**Source:** U.S. Green Building Council. LEED v4, 2016)

5. *Adequate daylight:* Intent is to reduce the use of electrical lighting by introducing daylight into space (*Points to award = 2.3865*)

   Requirements: Daylight factor at any interior point should be more than 2% and credit points are awarded according to Table 5.8

Table 5.8 Baseline data for Daylight factor

Daylight factor	Normalized points	Points to award
<2%	0	0
≥2% and <5%	0.5	1.19
≥5%	1	2.38

Source: IS SP 41 (S&T)

6. *Energy efficient Vertical transportation systems:* Intent is to save electrical energy by using energy-efficient transportation systems (*Points to award =2.46*).

Requirements: All the transportation systems (elevators, escalators, etc.) should be BEE certified.

5.5.5 Quantifying Sustainable Sites

1. Site selection: Intention is to encourage the construction in environmentally preferable locations and avoid the development of sensitive lands (*Points to award =2.35*).

Requirements: Points are distributed equally (1.18) for the following requirements.

- The building site should not consist of prime farmland.
- The building should not be located within a flood hazard area (*floodplain*).

2. Protect or restore habitat: Intention is to minimize the damage to the surrounding environment (habitat, species, water bodies, etc.) (*Points to award =2.23*)

Requirements: Points are distributed equally (1.11) for the following requirements

- The site should not be near the area which is home for species, listed as threatened or endangered.
- The building should be at least 100 feet (30m) away from a water body, defined as seas, lakes, rivers, streams, and tributaries that support or could support fish, recreation or industrial use.

3. Heat island reduction: Intention is to minimize effects on microclimates and human and wildlife habitats by reducing heat islands (*Points to award =2.04*).

Requirements: Ensure that at least 50% of *hardscapes* and roofs, but not including common roads that serve multiple buildings, on the project site come under shading or non-absorptive material. Points are awarded according to Table 5.9

Table 5.9 Points for percentage area with shading or non-absorptive material

The %age area under shading/non-absorptive material	Normalized points	Points to award
<50	0	0
≥50 and <75	0.5	1.02
≥75	1	2.04

(**Source:** U.S. Green Building Council. LEED v4, 2016)

4. Open space: Intention is to provide space for social interaction, physical activities, interaction with the environment, etc.

Requirements: Within half a mile (800m), there should be a publicly accessible or community-based open space that is at least 0.75 acre (0.3 hectares) or there should be publicly available space on the project site or there should be two smaller spaces of a 0.75 acre each (*Points to award =1.89*)

5. Light pollution (urban sky glow, light trespass, glare, clutter): Intent is to reduce outdoor light wastage and to curb the negative effects of light pollution on the surrounding environment (*Points to award =1.97*)

Requirements: Points are distributed equally (0.65) for the following requirements

- Street light luminaries must not emit any light above 90 degrees (horizontal).
- Illumination at property lines should be zero.
- There should be no up-lighting of trees.

4. *Conservation of soil surrounding the building (efficient drainage pattern, vegetative cover for topsoil, etc.):* Intent is to reduce soil pollution and to protect the soil from waterlogging (*Points to award =2.38*)

Requirements: Points are distributed equally (0.79) for the following requirements

- There should be proper top-soil laying for vegetative growth.
- Ensure proper and timely application of manure and fertilizers for the healthy growth of vegetation.
- Ensure good drainage system to avoid waterlogging.

5.5.6 Quantifying Social welfare

1. Awareness towards sustainable issues: Intention is to sustain the performance of the home by training its occupants in the operation and maintenance of equipment's, fixtures, etc (*Points to award =3.59*)

Requirements: Points are distributed equally (1.79) for the following requirements

- Product manufacturer's manuals for all installed equipment's, appliances, and fixtures should be available.
- Building owner and occupants should possess general information on the effective use of energy, water, and natural resources.

2.Efficient ventilation: Intention is to reduce the moisture problems and to avoid occupant's exposure to indoor pollutants from kitchens, bathrooms and other sources, by exhausting pollutants to outside and ventilating fresh air (*Points to award =3.73*)

Requirements: Points are distributed equally (1.86) for the following requirements

- Enhanced local exhaust/enhanced whole house ventilation system should be installed.
- There should be no unvented combustion appliance installed in the building (ovens and likes are excluded).

3. *Design for durability:* Intention is to ensure durability and performance of the building enclosure and its components and systems through appropriate design, materials selection, and construction practices (*Points to award =4.15*)

Requirements: Points are distributed equally (1.38) for the following requirements.

- Flooring in kitchen, bathroom, and laundry room and spa area should be waterproof.
- Maintain proper floor slope to drain out the accumulated water.
- Maintain enough cover for slabs, columns, and beams to protect the steel from corrosion (durability aspects of concrete).

5.5.7 Quantifying Transportation

1.Public transport accessibility: Intention is to reduce pollution and land development effect from automobile use (*Points to award =2.48)*

Requirements: Bus stop should be within 640 m radius. The following Table 5.10 details the accessibility to award points.

Table 5.10 Points for accessibility

Accessibility (in Kms)	Normalized points	Points to award
≥12	0.25	0.62
>=9 and <12	0.5	1.24
>=4 and <9	0.75	1.86
>=3	1	2.48

(**Source**: BREEAM SD5076: 0.1, (2014)

2.Use of bicycles by residents: Intention is to promote the use of bicycles and hence reduce automobile dependence. (Points to award = 2.39)

Requirements: Use of bicycles to the amenities nearby.

3.Proximity to amenities: Intention is to encourage the daily walking and bicycling and to reduce *Vehicle Miles Travelled* (VMT) and automobile dependence. (Points to award =2.17)

Requirements: The various amenities must be located within a radius of 800m from the building entrance and points are awarded according to Table 5.11

Table 5.11 Points for proximity to amenities

No. of amenities	Normalized points	Points to award
4-7	0.5	1.08
8-11	0.75	1.63
12 and above	1	2.17

(**Source:** U.S. Green Building Council. LEED v4, 2016)

4. Environmentally friendly pavements at the building site: Intention is to provide a porous surface at the building site to reduce the surface run-off (*Points to award =2.37*).

Requirement: Pavements should be made with one or more eco-friendly like Porous asphalt, Eco-friendly tiles, Plastic grid-pavers (highly permeable), etc.

5. *Reduced parking footprint:* Intention is to minimize the environmental harms associated with the parking facilities, including land consumption and rainwater runoff (*Points to award = 1.93*)

Requirement: Grounded level garages should be provided to accommodate parking facilities.

5.5.8 Quantifying Management

1. Managing the balance between the building and its immediate surrounding: Intention is to prevent the surrounding environment from degradation (*Points to award = 3.76*)

Requirements: Points are distributed equally (1.88) for the following requirements

- There should be no open waste disposal at the building site.
- There should be no harmful effluent discharged to the nearby water bodies.

2. Managing fire prevention facilities: Intention is to prevent property damage by fire Outbreak (*Points to award = 3.39*)

Requirements: Points are distributed equally (0.84) for the following requirements

- Fuel sources should be always kept in an isolated room to control ignition.
- A sound alarm system should be installed in the building.
- There should be an emergency exit (stairs).
- Fire extinguishers, fire hydrants, etc. should be installed.

3. Preventing the reckless dumping of polythene products at a building site: Intention is to make the site polythene free.

Requirement: Reckless dumping of polythene products at the building site should be prevented. If this parameter is not satisfied then zero points are awarded, if partially satisfied then 0.5 (normalized) points are awarded and if it is fully satisfied then full points are awarded. (*Points to award = 4.32*)

5.6 Significance of attribute performance

The performance of attribute with respect to their corresponding criteria is shown in Fig 5.5 to 5.12.

From Fig 5.5 it can be observed that attribute 'A1', Water monitoring and leak detection has the highest weight of 22.52% while 'A2' building water use reduction being the least (16.61%)

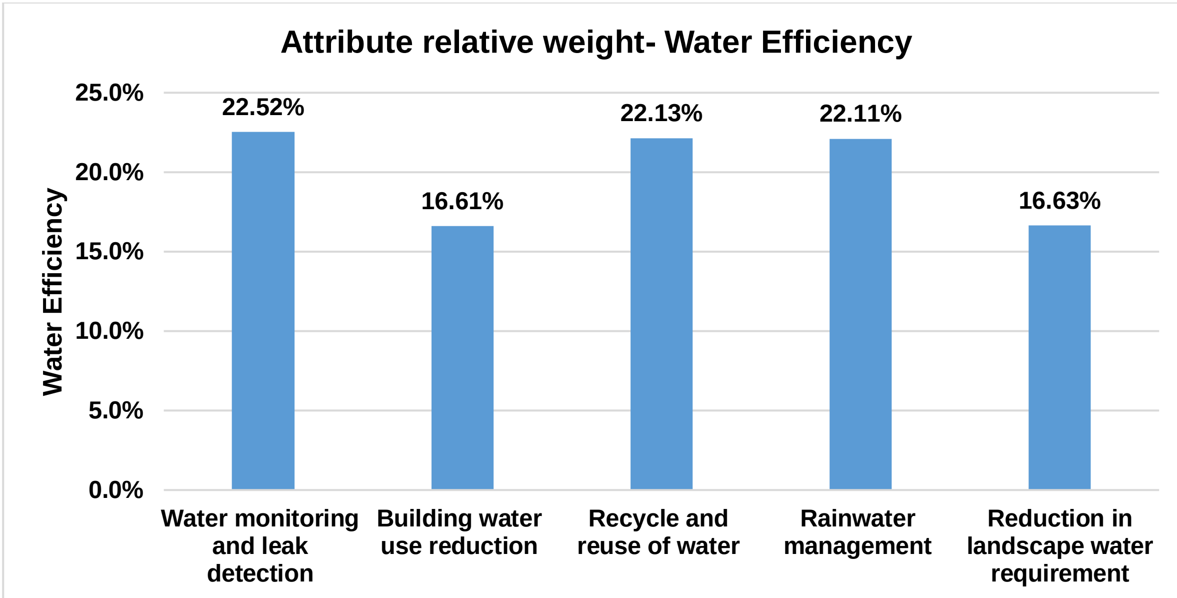


Fig. 5.5 Relative weights of attributes w.r.t Water Efficiency

Based on Fig 5.6, the attribute 'B2' regionally available materials has attained the highest weight of 21.56% while low-energy materials (B1) attained the least weight of 16.89%.

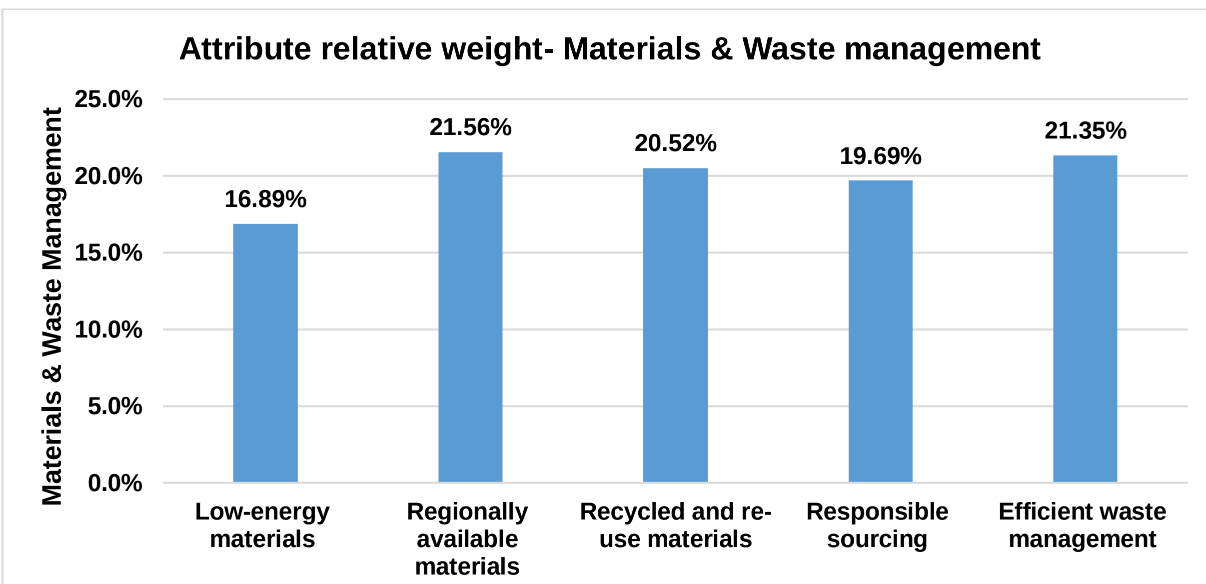


Fig. 5.6 Relative weights of attributes w.r.t Material & Waste Management

From Fig 5.7 it can be observed that attribute 'C3' was rated high with of 26.35% and 'C4' has the least weight of 23.57%.

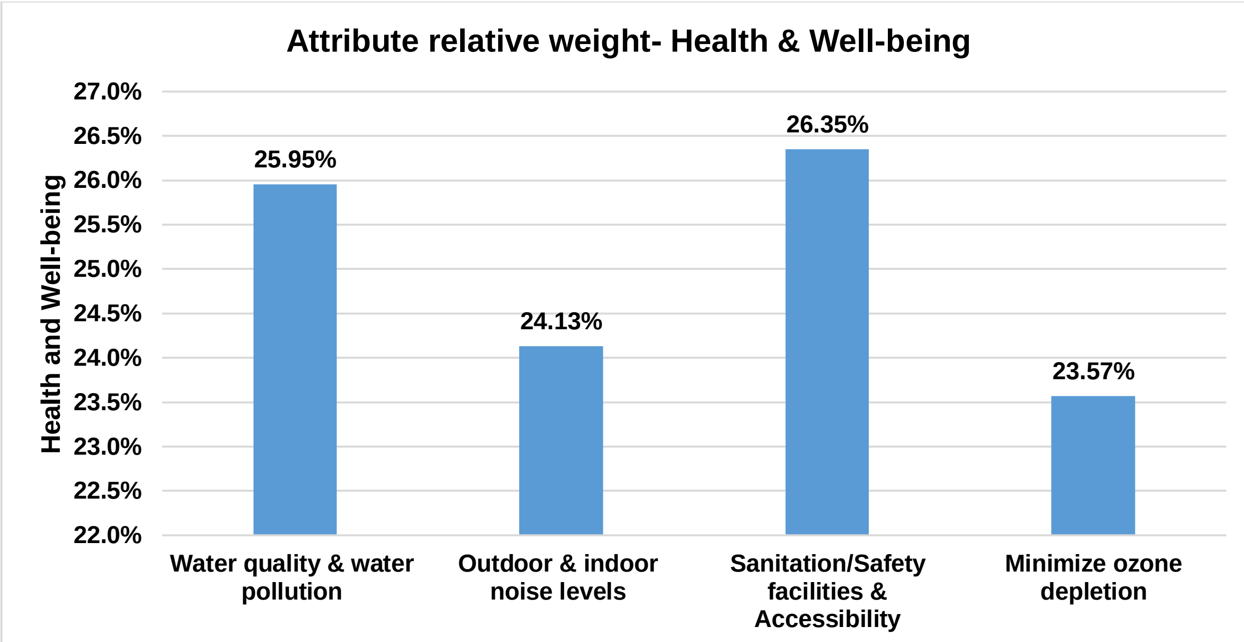


Fig. 5.7 Relative weights of attributes w.r.t Health & Wellbeing

Similarly, from Fig 5.8, the attribute 'D1' renewable energy production has the highest weight of 18.25% and 'D4'has lowest weight of 13.54%.

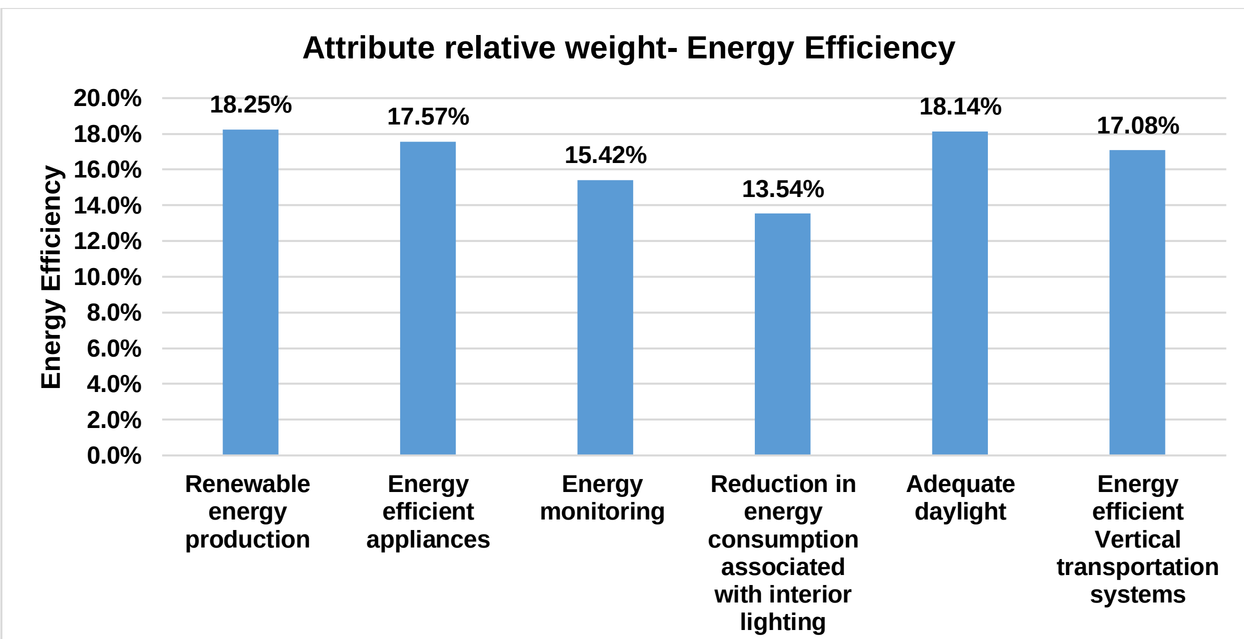


Fig. 5.8 Relative weights of attributes w.r.t Energy Efficiency

Based on Fig.5.9, it can be observed that attribute 'E7' attained the highest weight of 18.55% and 'E5' has the least weight of 14.70%.

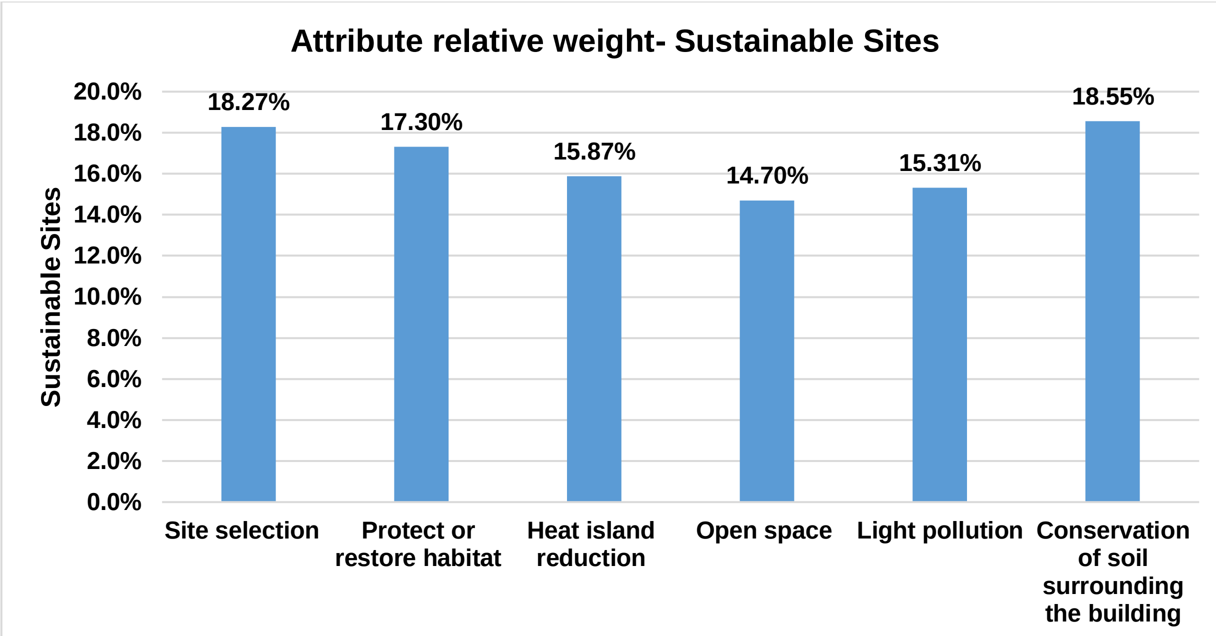


Fig. 5.9 Relative weights of attributes w.r.t Sustainable Sites

From Fig 5.10, it can be noted that attribute 'F3' design for durability was rated high with 36.17% and 'F1' has a lowest weight of 31.29%.

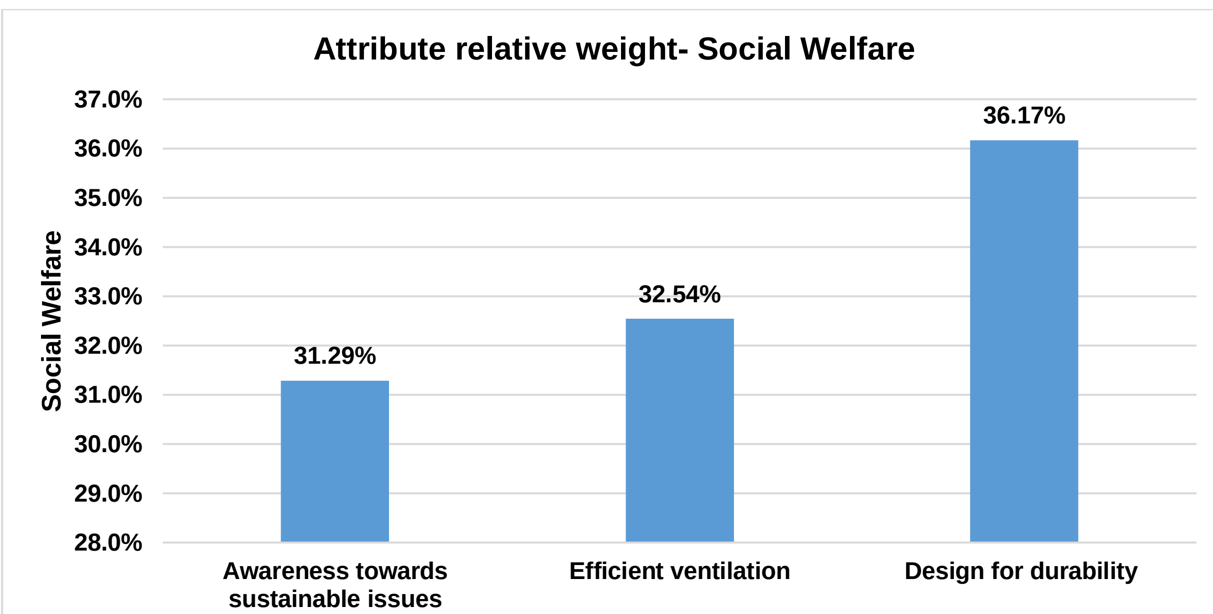


Fig 5.10 Relative weights of attributes w.r.t Social Welfare

Similarly, from Fig 5.11, it is noted that the attribute 'G1' Public transport accessibility has attained the highest weight of 21.83, while 'G5' has the lowest weight of 17.04%.

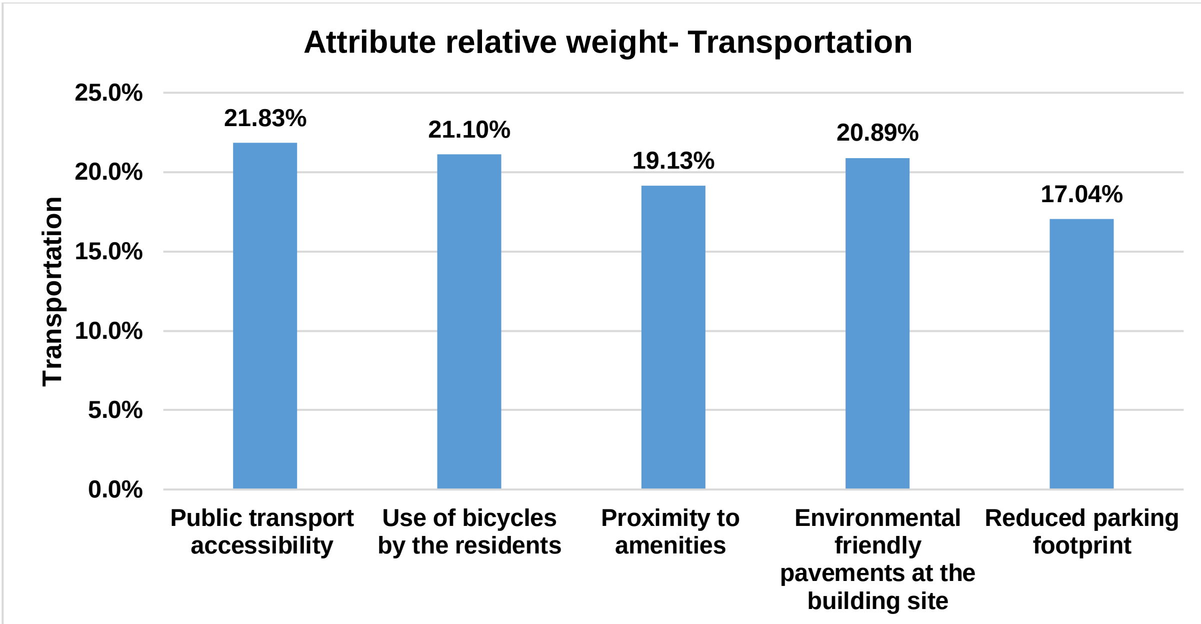


Fig. 5.11 Relative weights of attributes w.r.t Transportation

In the case of management criteria from Fig 5.12, it can be observed that attribute 'H3' has attained highest weight with 37.68% while 'H2', managing fire prevention facilities has least preferable weight of 29.57%

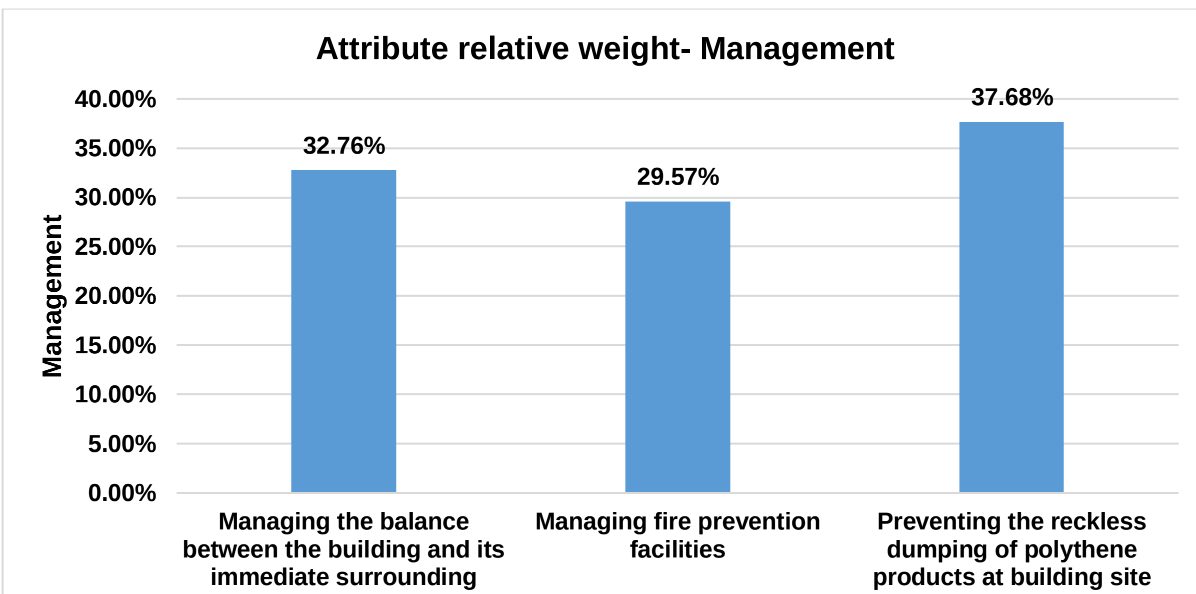


Fig. 5.12 Relative weights of attributes w.r.t Management

Among all the attributes, irrespective of criteria, the attribute 'D4' Reduction in energy consumption associated with interior lighting has the least weight of 13.54%, categorized under energy efficiency. Similarly, the attribute 'H3' Preventing the reckless dumping of polythene products at a building site has attained the highest weight of 4.32%, followed by the attribute ‘F3’ Design for durability with a weight of 4.15%.

5.7 Discussion on significance of the Sustainabe Building Assessment Tool (SBAT) weighing system

Within the Indian context, SBAT plays a significant role in promoting and achieving sustainability in the construction industry. Possible customization and adoption of relevant criteria from existing assessment tools are undertaken to suit the Indian environment. The relative weights are assigned for significant criteria and attributes by the key expert groups to influence the Indian sustainable objectives. It is hence required to discuss the prominence of the SBAT weighting system for Indian context about its divergence from existing tools by comparing the weights of criteria.

Assessment tools differ with different criteria and their priorities. Certain attributes may not be relevant outside the specific location. Therefore, assessment tools suited for one region may not be viable to be adopted in another region. An assessment tool should be designed in such a way that it prioritizes the needs and requirements of that specific region at that particular period.

5.7.1 Water Efficiency: Currently, Green Rating for Integrated Habitat Assessment (GRIHA), Indian Green Building Council (IGBC) are the two building assessment systems developed in India and Leadership in Energy and Environmental Design (LEED) is a recognized reference deployed from the US and managed by Indian Green Building Council (IGBC). The weighting system is the crucial step in developing an assessment system (Alyami, 2012). The LEED rating system has been criticized due to its inadaptability of the weighting system and for not being versatile to consider for specific regions. This spatial distribution of LEED criteria weights leads to uneven sustainable development. India being a water distress country should focus on water recycling, reuse, conservation, and harvesting to meet future demands. But LEED has lesser weights for water recycling, reuse, and recharge which does not suit the present and future scenarios of Indian water demands. LEED assigns 26 credits for sustainable sites, 35 credits for energy, and 14 credits for materials; while water efficiency offers only 10 possible credits. However, the GRIHA rating system has incorporated these requirements and weighted 18% with third highest weights among other criteria, but lags in quantifying the water efficiency. It completely relies on the document proof compliance which may lead to misconception and misjudgment. Therefore, to measure the water efficiency, National Building Code (NBC) of India IS SP 7: 2016 has updated some provisions related to water conservation and rainwater harvesting (NBC, 2016). The present study utilized some of these guidelines in quantifying the water efficiency to be adopted in the Indian context. Hence, the panel of expert's perception considers present and future water demands in weighing the water efficiency with a relative weight of 12.63% as shown in Fig 5.13 (a) – (d).

5.7.2 Materials and Waste Management:

The natural resources are getting depleted and becoming extremely rare. It is the impact of the human race to utilize them efficiently for the present generation and meets the demands of future generations. The current practices include the use of high embodied energy materials, such as cement, concrete, steel and so on in the building construction. Increased production of these materials leads to depletion of natural resources and virgin materials. The impacts caused by the material in various stages of its life cycle is addressed by life cycle inventory data, which is not available in India. It is known that material play a vital role in reducing the total embodied energy of the building in the operation and maintenance phase. So, the aim shall be to reduce, replace, and reuse the virgin materials, meaning encouraging the use of low embodied materials, utilize regional materials and industrial products. LEED has assigned less weight of 9% with respect to material and resources criteria, whereas GRIHA restricted the utilization of industrial by-products except for fly ash and assigned a weight of 13%, while in the present study, the materials and waste management criteria is assigned with a weight of 13.94% as shown in Fig 5.13 (a) –(d).

5.7.3 Health and Well-being:

Health and Well-being is a subjective criterion broadly expressed in terms of indoor air quality, light pollution, noise pollution, humidity, temperature, and comfort. GRIHA has assigned 12 points for occupant health and well-being and LEED has allotted 16 points. In the present work, those attributes which can measure quantitatively are only considered in health and well-being and allotted a weight of 13.04% as shown in Fig 5.13 (a) – (d).

5.7.4 Energy Efficiency:

India is the fourth largest consumer of energy in the world. The country should adopt efficient measures to curtail energy demands. The energy efficiency criterion is given a higher weight in both LEED and GRIHA assessments. In the present work, this criterion is given second top priority with a weight of 13.15% and satisfies the current concern of developing India's rapidly transforming building market towards environmental sustainability and save energy as shown in Fig 5.13 (a) – (d).

5.7.5 Sustainable Site:

Land is a limited resource and yet an essential resource for meeting the social, economic and environmental demands and targets. For countries such as India, that lack comprehensive and integrated land use planning system, there is a need for a customized approach. Ecologically, India has a varied climate with rich bio-diversity. Several buildings are built without concern to protect the existing biodiversity. It is the responsibility of the habitat to protect and preserve the heritage, culture and vegetative regions. Poor planning and encroachment of agricultural land leads to increased expenditure and stress on natural resources and ecological imbalance. The challenge lies in planning buildings in a densely developed area while striking a balance with nature. It is required to ensure that the basic amenities are allocated within some fixed radius of the selected site in order to reduce the burden on transportation fuel consumption and related emissions. For this criterion, LEED has allotted a weight of 7% and GRIHA has allotted 19% weight. In the present study it is weighted at 12.88%. There seems to a great difference in weights assigned by LEED, GRIHA, and the present SBAT system. Further, it was also observed that the expert's felt protecting and preserving bio-diversity in India can be achieved by giving relatively equal weight as other criteria and is shown in Fig 5.13 (a) – (d).

5.7.6 Social Welfare:

Sustainable buildings help to create an environment which is healthy and promotes the overall well-being of occupants. It brings nature near to the habitats and adopts eco-friendly practices. Neither of the assessments have considered this criterion directly, but they reflected the idea in the attribute social welfare indirectly through some of the criteria. But in the present study, this criterion has been considered separately to adapt to the

Indian regional context and the experts have addressed the benefits for the entire community by providing 11.48% of weight as shown in Fig 5.13 (a) – (d).

5.7.7 Transportation:

Transportation is an extensive system which generates large emissions. The prevalence of sound and air pollution is caused by transportation. In India, most of the cities are dominated by personal transport vehicles due to which environmental pollution is at a peak level and have crossed the threshold values. Further, this has given rise to parking footprint. Keeping this in view, the LEED rating system has assigned 15% weight for location and transportation criteria but GRIHA has completely ignored this criterion and indirectly assigned points to the permeable paving system. In the present study, SBAT incorporates transportation as a criterion to measure the public accessibility, enhance the use of bicycles, encourage eco-friendly pavements and reduced parking footprint on a weight of 11.36% as shown in Fig 5.13 (a) – (d).

5.7.8 Management:

It is the responsibility of the individual to manage the balance between the building and its immediate surrounding, preventing fire protecting hazards with minimum design strategies. Creating a provision for proper disposal of domestic waste and preventing the reckless dumping of polythene products nearby building is the basic idea in promoting clean sustainable development. Despite the existence of exhaustive guidelines and codes prepared by various national and state government bodies, the waste is not collected, segregated and disposed of in a proper manner. This causes both short-term as well as long damage to human beings exposed to them as well as to the ecology. The LEED rating system has assigned 2% weight to this criterion whereas GRIHA has not considered it directly, however, it includes the waste segregation attribute under waste management by allotting less weight of 1% overall as shown in Figure 5.13 (a) –(d). In the present SBAT system, importance is given to clean and organized environment and eco-system. The reduction in manmade hazards has given due importance in terms of waste disposal and segregation, reckless dumping of polythene products and waste water disposal with a weight of 11.49%.

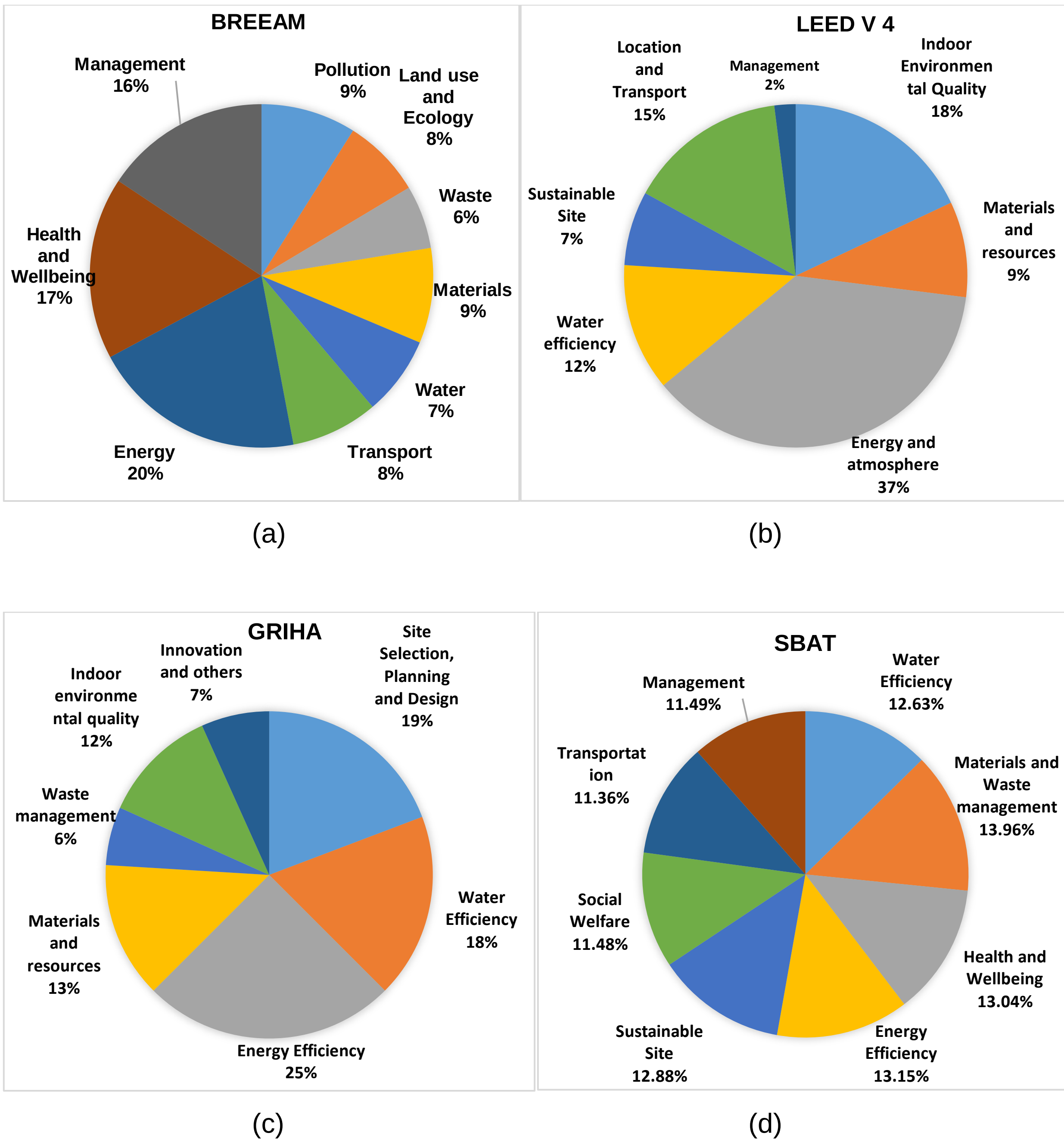


Fig. 5.13 (a)-(d) Comparison of criteria weight in BREEAM, LEED, GRIHA and SBAT assessment tools

Based on the sustainable assessment indicators derived, criteria and attributes, a scoring system was developed to evaluate Sustainable Building Score (SBS) of an existing building in Chapter 7.

5.8 Summary of Phase – II study

The present chapter concentrated on demonstrating the necessity of sustainable design and adoption of sustainable principles behind the transformation of conventional construction to sustainable construction in India. Based on the comparison of various assessment tools (LEED, BREEAM, GRIHA, and IGBC), it was observed that these rating systems are limited to regional context, climatic conditions, culture, heritage, and geographical conditions. The present chapter dealt with customizing and tailoring the existing assessment tools to suit the specific conditions in India. The attributes considered in the study can assess the building performance on a self-assessment basis.

The work involved quantitative assessment of criteria by establishing their associated attributes and pre-requisites. Based on the existing assessment tools, guidelines & policies and field practitioners', the pre-requisites were recognized keeping in view the regional content, culture, heritage, topographic features, and level of public awareness in India, to assess the attribute performance. This phase of work has reviewed the exiting tools, strengths, and weakness for implementing the possible ways to adopt in the Indian context. The present phase identified 8 criteria and 37 attributes, which are prominent and suitable for Indian context; the relative weights were determined using Fuzzy Analytical Hierarchy Process (FAHP) in assessing the sustainable performance of the building. The following are the specific conclusions derived from phase II study.

- The study has determined the relative weights of 37 attributes to assess the performance of eight criteria by integrating Fuzzy set theory and Analytical Hierarchy Process (AHP).
- The derived FAHP approach facilitated to capture the subjectivity, vagueness, and uncertainty of expert's perception.
- Among all the attributes, the study simplified 95% of attributes to quantify objectively, to measure the degree to which a building can achieve sustainable performance.
- Among all the 37 attributes, the attribute 'preventing and reckless dumping of polythene products' was prioritized with a highest global weight of 4.32 (37.68%); Secondly, 'design for durability' has weighed 4.15 (36.17%) followed by 'managing the building with surrounding environment' with a weight of 3.76 (32.76%).

- Considering Water Efficiency criteria, ‘water monitoring and leak detection’ has attained a high relative global weight of 2.84 (22.52%) followed by ‘recycle and reuse of water’ with a relative weight of 2.80 (22.13%).
- In the Materials and Waste Management criteria, the attribute ‘regionally available materials’ is rated high 3.01 (21.56%). Similarly, ‘sanitation facilities & accessibility’ is highly prioritized with 3.43 (26.35%) in Health and Well-being criteria.
- In Energy Efficiency criteria, the attribute ‘renewable energy production’ has attained a global weight of 2.40 (18.25%). Similarly, the attribute ‘soil conservation’ is highly prioritized with 2.39 (18.55%) in Sustainable Sites criteria.
- In Social Welfare criteria, the attribute ‘design for durability’ is highly prioritized with a global weight of 4.15 (36.17%). Similarly, the attribute ‘public transport accessibility’ was rated high with a weight of 2.48 (21.83%).
- Considering the Management criteria, the attribute ‘preventing reckless dumping of polythene products’ has attained a highest weight of 4.32 (37.68%).

The results of this study facilitate developing a scoring system to evaluate the Sustainable Building Score (SBS) keeping in view, the four SEET indicators. By integrating four sustainable indicators, eight sustainable criteria and 37 quantifiable attributes with supporting pre-requisites, the study developed a credit score and has evaluated the relative weight of attributes corresponding to each criterion. The novel method of assessment of building developed in this study takes into account the sensitivity to suit the practices, issues, and priorities of local to a certain region. The method is hence robust and is at the same time flexible.

It was observed that the attribute related to materials play a vital role in achieving building sustainability. To quantify material performance, the material Life Cycle Inventory (LCI) data is not available appropriately in developing countries like India. Hence, the selection of a sustainable material alternative, without the need for LCI data, is investigated and the same is presented in Chapter 6.

CHAPTER - 6

QUANTITATIVE ASSESSMENT OF BUILDING MATERIAL PERFORMANCE

Phase III

Objective: To evaluate the building material index considering sustainable SEET indicators, factors influencing material sustainable performance and material lifecycle phases, without the need for inventory data.

6.0 Material Background

In the previous chapters (4 & 5), the relative weights of sustainable criteria and the global weight of attributes are determined to assess sustainable building performance. Among the Eight sustainable criteria 'Materials & Waste Management (MW) criteria has secured the highest weight. The attributes under MW are difficult to quantify without the availability of life cycle inventory data which is the case in developing countries like India. The present chapter emphasizes on assessing the material performance both qualitatively and quantitatively.

Many operations in construction projects are responsible for the generation of a large amount of CO_2 emissions. The challenging job for a construction firm is to construct a structure which should help in enhancing user's quality of life and at the same time, it should reduce the impact on social, environmental and economic parameters. Thus, sustainable construction became an integral part of reducing the impact on social, economic and environmental aspects in developed and developing countries. To achieve sustainability in construction, selection of material plays an important role. With the growth in building and infrastructure facilities, the demand for materials and resources enhances leading to disturbance in the environment and destabilization in sustainability (Park et al. 2014). The challenge before the construction sector, hence, lies in providing building materials with reduced environmental burden. Also, the improved social benefit shall be economically feasible and technologically sustainable.

One of the important parameters of sustainable construction is the selection of sustainable material because materials are the major consumers of resources. Selection of good material is an essential part of good design. It is therefore necessary to think of sustainability evaluation methodologies for selection of sustainable materials. In the present scenario, the development of new and innovative material is necessitated to replace the conventional materials, as, they are creating a huge burden on the environment and also depletion of natural resources. Selection of a right material is important for functional use, design, performance, and practicability (Rao, 2008). Different materials may perform differently with respect to a single attribute. To choose an optimal material and achieve the desired results, it is important to evaluate a robust method to achieve the required performance.

6.1 Role of material in achieving building sustainability

India is a country with a fast-growing economy in the world (Dhull, 2018). The development and sustainability should go hand in hand to maintain global ecological balance. The green practices are in action to reduce the overall CO_2 emissions and are being implemented in the construction industry. Due to the availability of different material alternatives in the market and to achieve sustainability, practitioners feel difficulty in choosing the right material for what they are intended. Use of correct materials could reduce carbon emissions 30% (González & García Navarro, 2006). Unless and until the action for sustainable material consumption and implementation are enforced, energy consumption, waste, and Greenhouse Gas (GHG) emissions continue to grow further. Potential sustainable building materials are based on three sustainability indicators: environmental, social and economic. To design the product for our specific needs using Reduce, Reusable and Replaceable materials (3R), it is also important to find their technological properties as well as sustainable indicators (Bakhoum & Brown, 2012; Bank et al. 2011; Kisku et al. 2017).

6.2 Need for Material Life Cycle and Inventory data

The strategies to enhance sustainability is country specific and depends on its size, culture, and economic position (Šaparauskas & Turskis, 2006). For example, Al-Hajj & Hamani (2011), Govindan (2015) & Radhi (2010) in *UAE*, Wang et al. (2018) in *Taipei*, Ejiga, (2017) in *Lagos*, Abeysundara. (2009) in *Srilanka*, Akadiri, (2012) & Bakhoum & Brown, (2015) in *UK* have studied the country-specific parameters for assessing and selecting sustainable construction materials. In developed countries, the availability of material inventory data on environmental impacts throughout their lifecycle (raw material, manufacturing, transportation, construction, maintenance, repair, and demolition) makes the material evaluation approach versatile (Cole, 2005). The developed countries have been emphasizing on Life Cycle Assessment (LCA) but, these are location specific and cannot be utilized for others (Curran, 2012; Reap et al. 2008). There are several LCA based tools specific to a location like ATHENA in North America, ENVEST in the UK and every tool will be using the embodied Life Cycle Inventory (LCI) data to find the impacts of the materials (Trusty et al. 2002).

In developing countries like India, due to the availability of limited LCI data, it is difficult to analyze the material performance towards the environment. Also, LCA is a time-consuming process and does not consider socio-economic and technological impacts throughout the material lifecycle. Hojjati (2017), opines that it may not be an appropriate approach for assessing the material in terms of environmental impacts alone in developing countries like India. The need of the hour is hence, to select a material to reduce the environmental impacts, improve social well-being, improve economic viability and ensure Technological feasibility for achieving sustainability.

6.3 Multi-Criteria Decision Method (MCDM)

Multi-Criteria Decision Making (MCDM) provides an inclusive decision considering multiple factors and alternatives. Various approaches have been developed to facilitate the selection of appropriate material among the feasible alternatives. Shanian and Savadogo (2006), proposed a model using ELECTRE an outranking relationship concept which is quite extensive in the analysis. Rao (2007), developed a model based on a matrix approach and graph theory, which does not consider the judgment consistency of attributes. Manshadi et al. (2007), proposed a normalization model based on non-linear transformation with a digitally modified logic method for selection of material. However, this does not have a provision to assess the quantitative attributes. Chatterjee (2009), proposed VIKOR and ELECTRE for selection of materials. Khabbaz et al. (2009), proposed a method using fuzzy logic for selection of material, where it needs many IF-THEN rules which is cumbersome to compute. Maniya and Bhatt (2010), developed a Preference Selection Index (PSI) method for choosing an appropriate material, where the approach considers only objective weights of attributes and did not account their subjective weights. Jahan et al. (2012), developed a formula to determine the importance of factors based on interdependency relationship. Jahan and Edwards (2013), proposed a model with interval numbers and target-based factors in the VIKOR method for material selection problems where it was quite cumbersome to handle and understand. Liu et al. (2014), suggested an integrated DEMATEL based Analytical Network Process (ANP) a hybrid MCDM for factor evaluation and applied, modified VIKOR to improve the consistency of the results, which is very comprehensive to opt. Govindan et al. (2015), proposed a model for the selection of sustainable material using hybrid MCDM approach in UAE. Xue et al. (2016), projected a model for incomplete weight information using an interval-valued intuitionistic fuzzy set (IVIFSs) and multi-attributive border approximation area comparison (MABAC) for selection of material. It is noteworthy to observe that techniques like ELECTRE, VIKOR, TOPSIS, and AHP are widely spread MCDM techniques in the domain of material selection. However, each of them has their own limitations and purpose of application.

6.4 Sustainable factors and indicators

As the factor identification is an important aspect, the literature review related to sustainable performance associated with material selection by various MCDM based approach methods were identified and considered based on Social, Environmental, Economic and Technological aspects (SEET). A comprehensive review was carried out in available literature, guidelines and policies, and existing assessment tools and the 10 key sustainable factors which are mostly relevant to material assessment were considered (Table 6.1). Keeping in view SEET aspects, a thorough content analysis was conducted to assess the performance of building material towards sustainability. These sustainable factors are categorized with respect to quadruple-bottom line approach (i.e., SEET indicators) and a relation is established between them as shown in Table 6.2.

In the present study, three different MCDM methods are developed to observe the material prioritization based on the identified sustainable factors. Each method has its own significance and justification to use these methods and is described briefly in the following sections. A structured questionnaire survey was conducted to observe the importance of 10 sustainable factors and alternatives.

The sample size (n) is calculated based on Equations 6.1 (a & b). A population size (N) of 184 experts were contacted. Considering a confidence level of 95%, the corresponding z-score (z) is 1.96 and Population proportion (p) 0.5; margin of error (ϵ) as 10%, the sample size (n) is estimated as 63.

(If population size, N is unknown) $n = \frac{z^2 * p(1-p)}{\epsilon^2}$ Eq. 6.1a

(If population size, N is known) $n' = \frac{n}{1 + \frac{z^2 * p(1-p)}{\epsilon^2 N}}$ Eq. 6.1b

In the present work, a total of 184 professionals were contacted, and 120 responses were received, among them 54 responses were found to be appropriate and reliable (Appendix D). These include Academicians, Designers, Architects, Consultants, Engineers and other experts. All the methods utilized the same input data set. For each method, an example is illustrated considering a case of selection of sustainable material among five different alternatives of binder material which will facilitate to achieve a sustainable concrete. The prominently used binder material alternatives – Ordinary Poland Cement (OPC), Pozzolonic Portland Cement Fly ash based (PPC-F), Pozzolonic Portland Cement Slag based (PPC-S), Geopolymer (GP) and Composite Cement (CC) have been selected based on the expert's advice from various technical, industrial and academic institutions.

Table 6.1 Sustainable factors considered by various researchers

Factors	Key Reference
Climate Change	Vij et al. 2010; Bhattacharjee, 2010; Al-Ghamdi & Bilec, 2017; Crawford, 2011; Govindan et al. 2015; Vinodh et al. 2014;
Pollution and Emissions	Akadiri & Olomolaiye, 2012; Bakhoum & Brown, 2012; Grace K.C. Ding, 2008; Huang et al. 2015; Kylili et al. 2016.
Construction and Demolition Waste	Rahman et al. 2016; Akadiri & Olomolaiye, 2012; Chatterjee, 2009; Collins, 2010; Crawford, 2011; Khatib, 2009; Zhong & Wu, 2015
Consumption of resource	Akadiri & Olomolaiye, 2012; Akadiri; Alyami & Rezgui, 2012; Cole, 2005; CPWD, 2014; G. K C Ding, 2013; Grace K.C. Ding, 2008; Khoshnava et al. 2016; Kylili et al. 2016; Sabaghi et al. 2016;

Life Cycle Cost	Akadiri et al. 2013; Alleviation, 2015; Ashby, 2013; Bakhoum & Brown, 2015; G. K C Ding, 2013; Gilbert et al. 2002; Khoshnava et al. 2016; Sabaghi et al. 2016; Zhong & Wu, 2015
Recyclability and Reusability	CPWD, 2014;G. K C Ding, 2013; Gao et al. 2010; Mayyas et al. 2016; Sabaghi et al. 2016; Valenzuela-Venegas et al. 2016
Local Development	Akadiri & Olomolaiye, 2012; Akadiri et al. 2013; Bakhoum & Brown, 2013; Gilbert et al. 2002; Sabaghi et al. 2016; Shi et al. 2013; Vinodh et al. 2014
Health & Safety	ALwaer & Clements-Croome, 2010; Anadon et al. 2016; Bakhoum & Brown, 2012, 2013; Hara et al. 2016; Heraviet al. 2017; Kylili et al. 2016;
Practicability & Flexibility	Ashby, 2013; Bakhoum & Brown, 2012, 2013; Sarachaga et al. 2017; Florez et al. 2013; Jakhar & Barua, 2014; Kannoorpatti & Surovtseva, 2015;
Human Satisfaction	Akadiri & Olomolaiye, 2012; Akadiri et al. 2013; Bakhoum & Brown, 2012, 2013; Zhou & Castro Lacouture, 2011

Table 6.2 Relation between Sustainable factors and Indicators

	Factors	**Environmental**	**Economical**	**Social**	**Technological**
C1	Climate change	✓			
C2	Pollution and emissions	✓			
C3	Construction and demolition waste	✓			
C4	Consumption of resource	✓	✓		
C5	Cost		✓		
C6	Recyclability and Reusability	✓	✓		✓
C7	Local development		✓	✓	
C8	Human health and safety			✓	
C9	Practicability		✓		✓
C10	Human satisfaction	✓		✓	
Total no of indicators related to indicators		**6**	**5**	**3**	**2**

(**Source:** Akadiri & Olomolaiye, 2012; Bakhoum & Brown, 2012; Bansal et al. 2015; BMTPC, 2015.; Khatib, 2009; Vinodh et al. 2014; Weisbrod et al. 2015)

6.5 Method I : Entropy-based Fuzzy Technique for Order Preference by Similarity to Ideal Solution (EFTOPSIS)

The determination of the weight of factors is an integral part of decision-making evaluation. It is necessary to consider objective and subjective weights in choosing sustainable material. Considering the concepts of Entropy, Fuzzy set theory and TOPSIS, the study developed a framework to assess the material performance.

The present work is to develop a conceptual framework by integrating the subjective and objective weights utilizing the concepts of Fuzzy set theory and Entropy and then selecting a sustainable material by means of FTOPSIS approach (Fig. 6.1). The objective weights of factors are evaluated using the Entropy method, while the subjective weights are evaluated using Trapezoidal Fuzzy membership functions. Keeping in view of the physical, mechanical, design specifications and durability aspects, the decision maker finds the factors based on the purpose and application of a material.

6.5.1 Entropy

The statistical concept of entropy was introduced by Shannon and Weaver (1949) in information theory and transmission. Shannon's entropy evaluates the expected information of a certain statement. The measure of average uncertainty is named as Entropy. It is a measure of the degree of uncertainty characterized by a discrete probability distribution ($p_i,\ldots,p_k$). It can be stated that large variation in distribution among p_i's consists of precise information rather than the distribution with small variations (Chan and Wu, 2005). In other words, higher the Entropy (E_j), higher is the uncertainty and smaller is the variance ($p_i,\ldots,p_k$) and vice-versa. Less information means less uncertainty. Entropy will be maximum when all the alternatives perform the same based on a factor. The factor having the highest importance should be assigned the highest priority. The study evaluates the subjective and objective weights of factors in assessing the performance of material sustainability. The model captures the subjectivity of the decision maker's opinion irrespective of experience.

The performance rating of a certain number of alternatives needs some amount of information on a number of factors. Let x_{ij} be the rating corresponding to j^{th} factor for an i^{th} alternative. Then $x_j = \sum_{i=1}^{m} x_{ij}$ is the aggregated score for all respondents. The following three steps will describe the calculation of Entropy weights (Dos Santos et al., 2018).

Step 1: Normalization of the decision matrix

Normalization is a technique to reduce the decision-making elements to dimensionless and comparable values. The decision matrix is normalized to get projected indices (P_{ij})

using Equation 6.2. Here, x_{ij} signifies the performance of i^{th} alternative with respect to j^{th} factor.

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (i = 1, 2,...., m; j = 1, 2,...., n) \qquad \text{(Eq 6.2)}$$

Step 2: Compute the Entropy measure (E_j)

$E_j = -k \sum_{i=1}^{m} P_{ij} \, log \, P_{ij}$ where k = 1/ log(m) is a positive constant that ensures the value of E_j to lie between 0 and 1. (Eq 6.3)

Step 3: Determination of Objective weight (φ_j)

$$\varphi_j = \frac{1-E_j}{\sum_{j=1}^{n}(1-E_j)} \qquad \text{(Eq 6.4)}$$

When all the factors perform the same, then φ_j has zero variations.

6.5.2 Fuzzy numbers and Linguistic terms

Lofti Zadeh (1965), introduced Fuzzy set theory in order to make decisions for problems dealing with vagueness, subjectivity, and imprecision. The fuzziness comes into play when the judgment is not well defined and doesn't have proper boundary/limit. In fuzzy set theory, each element is assigned with a membership value to determine the degree to which the element belongs to a fuzzy set ranging from 0 to 1. The concept of quantitative evaluation using linguistic terms is subjective in nature and involves vagueness. For this, the fuzzy set theory captures and resolves the ambiguity involved in the judgment.

The fuzzy set denoted by 'A' is defined by $\mu_A(x)$: $X \rightarrow [0,1]$ on the universe of discourse, where each element of 'x' is well-defined to a membership value $\mu_A(x)$ between 0 and 1. When $\mu_A(x)=0$ the element x does not belong to set A and when $\mu_A(x) =1$ the element x absolutely belongs to set A. Since there does not exist absolute membership values, subjectivity is assessed based on the context. In the present study, the trapezoidal fuzzy number is preferred to handle the subjectivity of the decision maker.

Definition 1: A fuzzy trapezoidal number is defined as A= (p, q, r, s) where 'p' represents a lower limit, 'q' represents lower support limit, 'r' represents upper support limit and 's' represents an upper limit and $p \leq q \leq r \leq s$ (Fig 6.1).

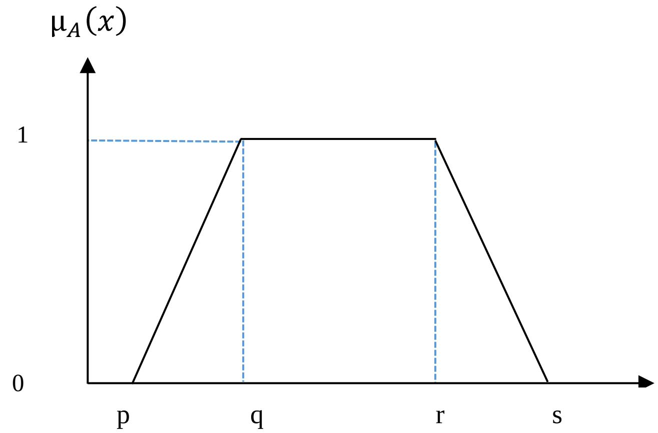


Fig 6.1 Trapezoidal fuzzy number

Here, the x-axis defines the universe of discourse and y-axis represents the degree of membership in the interval [0,1] (Zimmermann 2001).Then the membership function of $\mu_A(x)$ is defined as

$$\mu_{\boldsymbol{A}}(\boldsymbol{x}) = \begin{cases} \mathbf{0}, & x < p \\ \frac{x-p}{q-p}, & \mathbf{p} \leq x \leq \mathbf{q} \\ \mathbf{1}, & \mathbf{q} \leq x \leq \mathbf{r} \\ \frac{s-x}{s-r}, & \mathbf{r} \leq x \leq \mathbf{s} \\ \mathbf{0}, & x \geq \mathbf{s} \end{cases} \quad \text{(Eq. 6.5)}$$

In a trapezoidal fuzzy number, if q = r, then the fuzzy number becomes a triangular fuzzy number. A linguistic variable is a term describing quantitative expressions dealing with vagueness and uncertainty (Sarkar & Singh, 2019). In the present study, the linguistic terms are assigned to a trapezoidal membership value (Table 6.1).

Definition 2: Given two trapezoidal fuzzy numbers $\widetilde{P_1}$ and $\widetilde{P_2}$, where $\widetilde{P_1}$ = (p_1, q_1, r_1, s_1) and $\widetilde{P_2}$ = (p_2, q_2, r_2, s_2), the operation laws of addition, multiplication, division and reciprocal are defined by Equations 6.5 to 6.8.

$$\widetilde{P_1} \oplus \widetilde{P_2} = (p_1+p_2;\ q_1+q_2;\ r_1+r_2;\ s_1+s_2) \quad \text{(Eq. 6.6)}$$

$$\widetilde{P_1} \otimes \widetilde{P_2} = (p_1 \otimes p_2;\ q_1 \otimes q_2;\ r_1 \otimes r_2;\ s_1 \otimes s_2) \text{ for } p_1 > 0;\ q_1 > 0;\ r_1 > 0;\ s_1 > 0 \quad \text{(Eq. 6.7)}$$

$\widetilde{P_1}/\widetilde{P_2}$= ($p_1/s_2$; r_1/r_2; s_1/s_2; s_1/p_2) for $p_1>0$; $q_1>0$; $r_1>0$; $s_1>0$ (Eq. 6.8)

$\tilde{P}_1^{-1}$= ($1/s_1$; $1/q_1$; $1/r_1$; $1/p_1$) for $p_1>0$; $q_1>0$; $r_1>0$; $s_1>0$ (Eq. 6.9)

Definition 3: The simple and lucid method proposed by Liu et al. (2014) to calculate distance between two trapezoidal fuzzy numbers using vertex method is given as

Distance $d(\widetilde{P_1}, \widetilde{P_2}) = \sqrt{\frac{1}{4}[(p_1 - p_2)^2 + (q_1 - q_2)^2 + (r_1 - r_2)^2 + (s_1 - s_2)^2]}$ (Eq. 6.10)

Table 6.3 Crisp value, Linguistic terms, and Trapezoidal Membership values for factor and Alternative Evaluation

Crisp Value	Linguistic terms for factor evaluation	The linguistic term for Alternative Evaluation	Fuzzy Trapezoidal Membership value
7	Very high importance (VH)	Very Good (VG)	(9, 10, 11.5, 11.5)
6	High importance (H)	Good (G)	(7.5, 8.5, 9.5, 10.5)
5	Above moderate importance (AM)	Moderate Good (MG)	(6, 7, 8, 9)
4	Moderate importance (M)	Fair (F)	(4.5, 5.5, 6.5, 7.5)
3	Below moderate importance (BM)	Moderate Good (MG)	(3, 4, 5, 6)
2	Low importance (L)	Poor (P)	(1.5, 2.5, 3.5, 4.5)
1	Very low importance (VL)	Very Poor (P)	(0.5, 0.5, 2, 3)

6.5.3 Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS)

The objective weights of the factors are evaluated using the entropy method, while the subjective weights are evaluated using fuzzy membership functions defined by linguistic variables and converted to trapezoidal fuzzy numbers. It was observed that Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), needs less mathematical effort in tackling the problem of material selection considering conflicting factors (Jahan et al. 2011, 2012). The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a useful technique for ranking and selecting the alternatives among a number of possibilities. The method is based on the principle that the distance from the ideal solution is the shortest from the positive solution and farthest from a negative solution. In other words, the solution which maximizes the benefits and minimizes the cost parameter is the main factor.

The advantage of the fuzzy approach is that, it, facilitates to aggregate the multiple decision makers (Torfi et al. 2010). Since, the subjective preferences for factor evaluation are the anticipated solution for unquantifiable variables assigned with fuzzy numbers and involved with multiple decision makers, fuzzy TOPSIS method is an ideal method for resolving such problems (Chen et al. 2006). The methodological framework to assess the material sustainable performance is shown in Fig 6.2.

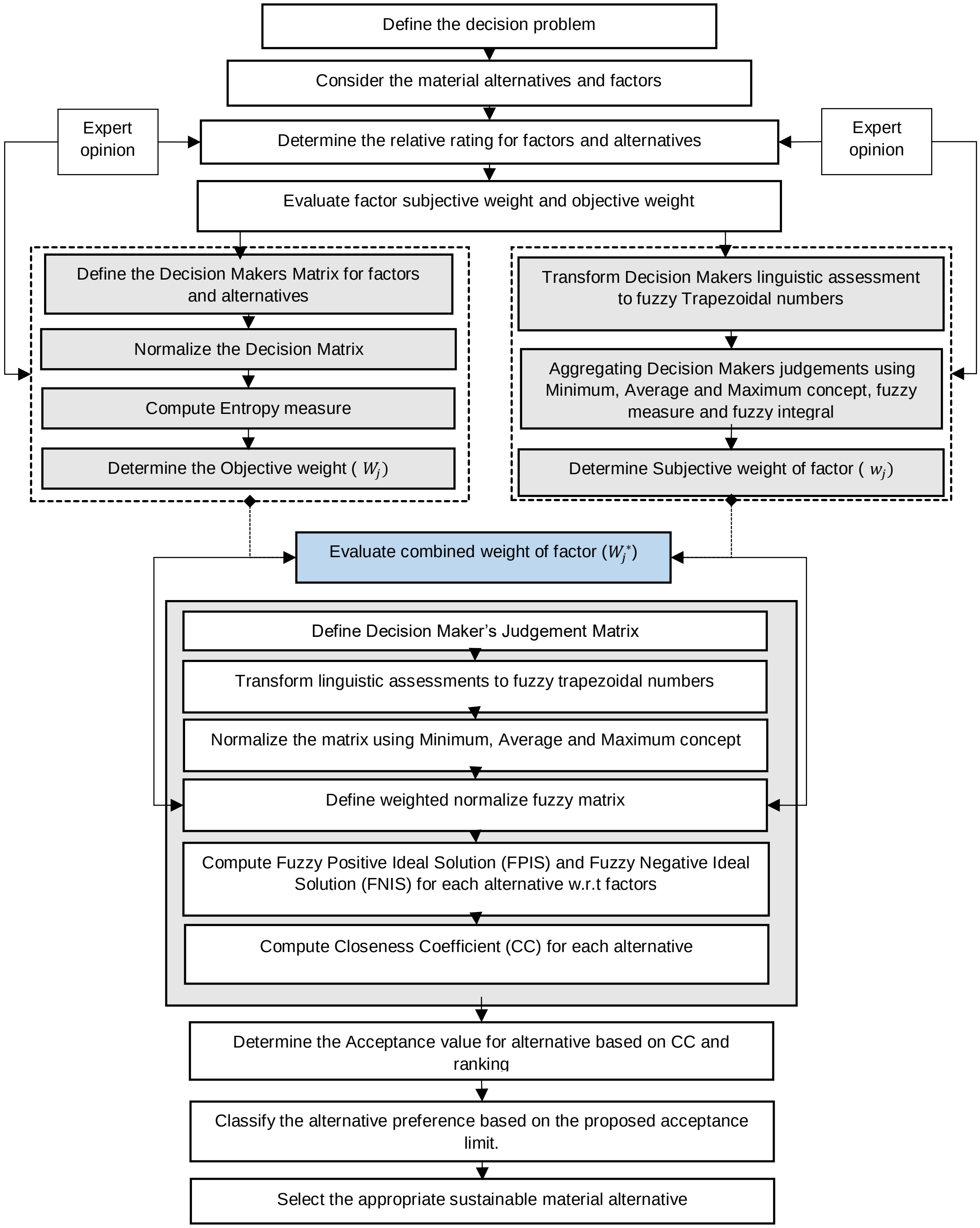


Fig. 6.2 Schematic diagram for Development of a framework to assess Sustainable Performance

6.5.4 Fuzzy TOPSIS Approach

The fuzzy TOPSIS approach is briefly described in the following steps:

Step 1: Let 'm' alternatives be denoted by A_i{i=1,2,…m} with regard to 'n' factors C_j{j= 1,2,…n} and having 'K' decision group members, then the fuzzy rating of the k^{th} decision member for alternative 'A_i' and factor 'C_j' is represented as x_{ij}^k = ($p_{ij}^k, q_{ij}^k, r_{ij}^k, s_{ij}^k$) where x_{ij}, represents trapezoidal fuzzy number denoted by $(p_{ij}, q_{ij}, r_{ij}, s_{ij})$.

Similarly, the weight of the factor is denoted by C_j^k = ($w_{j1}^k, w_{j2}^k w_{j3}^k, w_{j4}^k$)

Step 2: The rating given by decision makers are aggregated with respect to i^{th} alternative and j^{th} factor and are calculated using Equation 6.11 and expressed as $x_{ij} = (p_{ij}, q_{ij}, r_{ij}, s_{ij})$.

$$p_{ij} = min_k\{p_{ij}^k\}, \ q_{ij} = \frac{1}{K}\sum_{k=1}^{K}\{q_{ij}^k\}, r_{ij} = \frac{1}{K}\sum_{k=1}^{K}\{r_{ij}^k\}, \ s_{ij} = max_k\{s_{ij}^k\} \qquad \text{(Eq 6.11)}$$

where, $x_{ij}^k = (p_{ij}^k, q_{ij}^k, r_{ij}^k, s_{ij}^k)$ is the fuzzy relative importance rating of k^{th} decision maker covering various degrees of importance.

The fuzzy decision matrix is then concisely expressed in terms of factors and alternatives reducing multiple decision makers using Equation 6.12 as follows

$$\mathrm{P}\ (x_{ij})_{m \times n} = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix} \qquad \text{(Eq 6.12)}$$

Similarly, the fuzzy subjective factor weight of the decision makers is aggregated and expressed as $w_j = (w_{j1}, w_{j2}, w_{j3}, w_{j4})$ using Equation 6.13

where $w_{j1} = min_k\{w_{j1}^k\}$, $w_{j2} = \frac{1}{K}\sum_{k=1}^{K}\{w_{j2}^k\}$, $w_{j3} = \frac{1}{K}\sum_{k=1}^{K}\{w_{j3}^k\}$, $w_{j4} = max_k\{w_{j4}^k\}$ (Eq 6.13)

where, $w_{ij}^k = (p_{ij}^k, q_{ij}^k, r_{ij}^k, s_{ij}^k)$ is the fuzzy relative importance rating of k^{th} decision maker for j^{th} factor covering various degrees of importance.

Then, the combined weight (W_j^*) obtained from subjective (w_j) and objective (φ_j) weights calculated using Equation 6.14.

$$W_j^* = \varphi_j \times w_{j(1,2,3,4)} \qquad \text{(Eq 6.14)}$$

Step 3: Normalization of fuzzy decision matrix 'P' to obtain the normalized matrix R = [r_{ij}] using Equations (6.15 (a) & (b)).

$r_{ij} = (\frac{p_{ij}}{s_j^*}, \frac{q_{ij}}{s_j^*}, \frac{r_{ij}}{s_j^*}, \frac{s_{ij}}{s_j^*})$Where, $s_j^* = max_i\{s_{ij}\}$(for all j belongs to benefit factor); (Eq 6.15a)

$r_{ij} = (\frac{p_j^-}{s_{ij}}, \frac{p_j^-}{r_{ij}}, \frac{p_j^-}{q_{ij}}, \frac{p_j^-}{p_{ij}})$Where, $p_j^- = min_i\{p_{ij}\}$ (for all j belongs to non-beneficial factors);

(Eq 6.15b)

Step 4: Compute the normalized weighted fuzzy decision matrix using Equation 6.16

$$V_{ij} = R \times W_j^* \quad \text{(Eq 6.16)}$$

Step 5: Determine the Fuzzy-Positive Ideal Solution (FPIS) & Fuzzy-Negative Ideal Solution (FNIS).

FPIS (A*) = $(a_1^*, a_2^*, a_3^* \dots \dots a_n^*)$, where $a_j^* = max_i\{a_{ij4}\}$; (Eq 6.17)

FNIS (A-) = $(a_1^-, a_2^-, a_3^- \dots \dots a_n^-)$, where $a_j^- = min_i\{a_{ij1}\}$;

Step 6: Using the vertex method, the distances are calculated from Equation 6.18.

$$d_i(x, y) = \sqrt{\frac{1}{4}[(p_1 - p_2)^2 + (q_1 - q_2)^2 + (r_1 - r_2)^2 + (s_1 - s_2)^2]} \quad \text{(Eq 6.18)}$$

The distance from the normalized weighted matrix of an alternative (A_i) to the corresponding FPIS & FNIS is evaluated using Equations (6.19 & 6.20).

$$d_i^* = \sum_{j=1}^{n} d(a_{ij}, a_j^*) \quad \text{(Eq 6.19)}$$

$$d_i^- = \sum_{j=1}^{n} d(a_{ij}, a_j^-) \quad \text{(Eq 6.20)}$$

Step 7: Compute the Closeness Coefficient (CC_i) for each alternative (A_i) using (Equation 6.21)

$$CC_i = \frac{d_i^-}{(d_i^- + d_i^*)} \quad \text{(Eq 6.21)}$$

Based on the Closeness Coefficient (CC_i), the geometric distance of alternative from FPIS and FNIS, the priority of the alternatives is determined. Higher the Closeness Coefficient (CC_i), better is the alternative towards the ideal solution.

6.5.4 Illustration of an example

In order to assess the relative weight of conflicting factor based on subjective and objective preference and thereby, select a suitable binder material alternative for sustainability, the present study has identified 10 significant factors keeping in view the Social, Environmental, Economic and Technological aspects (SEET). The factor objective weight is evaluated from the data collected from 54 respondents. These include Academicians, Designers, Architects, Consultants, Engineers and construction industry of construction experts. While the subjective weight of factor is resolved by considering expert views from Academia, Design, Architecture, and Engineering background having not less than 20 years of experience in the relevant subject field and who are continuously involved in handling sustainability issues related to the construction industry.

The relative rating for factor evaluation is summarized using the proposed linguistic terms (Table 6.4). Defining the decision-making problem and the steps involved in the computation are summarized below.

Step 1: From the proposed trapezoidal membership functions for criterion evaluation (Fig 6.3), the Decision Maker (DM) rates the importance of each criterion by means of fuzzy linguistic term (Table 6.3).

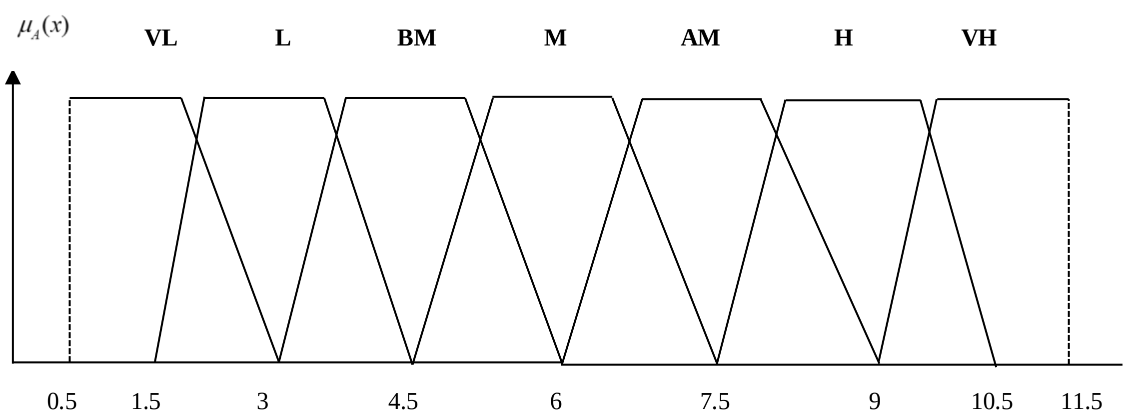


Fig. 6.3 Trapezoidal Fuzzy membership functions for evaluating factor

The crisp rating involved with subjectivity and vagueness given by the decision makers as 'w_j' is transformed to the trapezoidal fuzzy number. Then, the trapezoidal fuzzy weight of factor with respect k^{th} decision maker become C_j^k = ($w_{j1}^k, w_{j2}^k w_{j3}^k, w_{j4}^k$). Therefore, the aggregated fuzzy subjective weight of 4 sets of expert decision makers is evaluated using Equation 6.12 and are shown in Tables (6.4 & 6.5).

Table 6.4 Average relative weights of factors by Decision Makers

	DM-1	DM-2	DM-3	DM-4
	Academicians	**Designers**	**Architects**	**Engineers**
C1	VH	VH	VH	VH
C2	VH	H	H	VH
C3	H	VH	VH	H
C4	VH	VH	VH	VH
C5	H	AM	M	H
C6	H	AM	AM	H
C7	AM	M	AM	BM
C8	VH	AM	VH	M
C9	AM	M	AM	AM
C10	H	VH	H	VH

Table 6.5 Aggregated fuzzy weights of decision makers for evaluation of factors

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
w_{j1}	9.00	7.50	7.50	9.00	4.50	6.00	3.00	4.50	4.50	7.50
w_{j2}	10.00	9.25	9.25	10.00	7.375	7.75	5.875	8.125	6.625	9.25
w_{j3}	11.50	10.50	10.50	11.50	8.375	8.75	6.875	9.375	7.625	10.50
w_{j4}	11.50	11.50	11.50	11.50	10.50	10.50	9.00	11.50	9.00	11.50

Step 2: The ratings of 54 respondents with respect to alternatives and factors are considered to determine the objective Entropy weight. The average rating matrix is determined with respect to factors and the alternatives as shown in Table 6.6. The objective weight of factor is obtained from Equations (6.3 & 6.4) and is shown in Table 6.7. Higher E_j value indicates the priority of the corresponding φ_j. It is observed that Practicability & Flexibility (C10) and Global warming Potential (C1) has secured higher weights for evaluating the sustainable binder material, whereas, Local development (C7) and Human health and safety (C8) secured the least weight. This type of prioritization of factors helps in policy making for implementing sustainable practices.

Table 6.6 Objective ratings for evaluating factors

Alternative / factor	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
A1	4.07	3.72	4.52	3.50	3.85	3.33	4.24	3.33	3.21	3.20
A2	3.20	3.07	3.81	2.46	2.83	3.85	4.63	3.46	4.70	5.30
A3	4.50	3.76	4.59	3.46	3.78	3.81	4.57	3.56	4.39	4.50
A4	3.12	4.69	4.69	3.94	2.96	3.57	4.44	3.19	3.74	4.84
A5	4.56	4.17	4.48	3.52	3.24	3.63	4.72	3.43	3.98	3.80

Table 6.7 Entropy Weight of factor (Objective)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
E_j	0.9920	0.9941	0.9984	0.9931	0.9952	0.9992	0.9996	0.9996	0.9947	0.9905
W_j	**0.1837**	**0.1351**	**0.0362**	**0.1588**	**0.1103**	**0.0189**	**0.0098**	**0.0099**	**0.1205**	**0.2169**

Step 3: The Decision Maker (DM) rates the importance of each alternative with respect to each factor by means of fuzzy linguistic terms (Fig 6.4). Then, the aggregated fuzzy rating of 54 decision makers is evaluated using Equation 6.10 and the same is shown in Table 6.8.

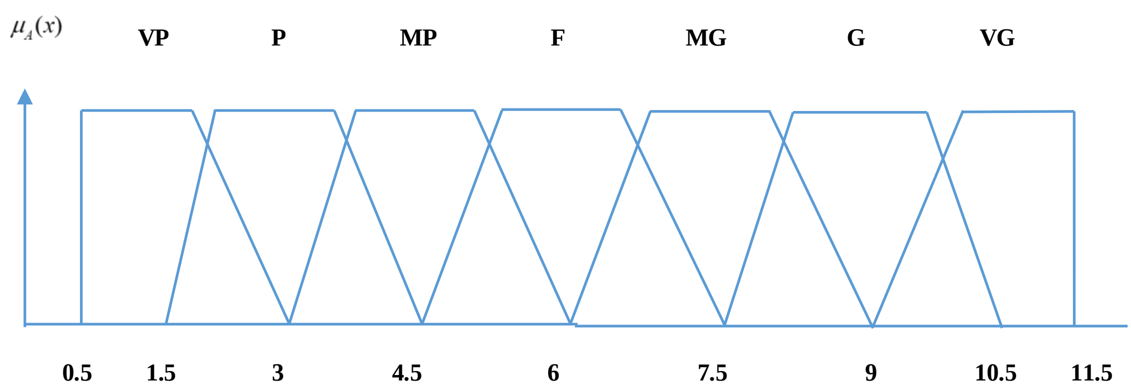


Fig. 6.4 Fuzzy trapezoidal membership function for evaluating alternative

Step 4: The normalized fuzzy decision matrix is obtained from Equations (6.15 (a) & (b)) and is shown in Table 6.9.

Step 5: The combined subjective and objective normalized weighted matrix of factor is obtained by using Equation 6.14 and is represented in Table 6.10.

Table 6.8 Aggregated Fuzzy weighted matrix for an alternative with respect to evaluation of factors

ALTERNATIVES	CLIMATE CHANGE (C1)				POLLUTION (C2)				SOLID WASTE (C3)				RESOURCE CONSUMPTION (C4)				COST (C5)			
A1	1.5	7.17	8.21	11.5	3	6.89	7.93	11.5	0.5	5.73	6.77	11.5	3	7.83	8.92	11.5	1.5	7.25	8.27	11.5
A2	0.5	5.38	6.41	11.5	1.5	5.92	6.93	11.5	0.5	4.69	5.73	11.5	1.5	6.25	7.26	11.5	0.5	5.71	6.73	11.5
A3	1.5	5.14	6.16	11.5	1.5	5.86	6.87	11.5	0.5	4.58	5.62	11.5	1.5	6.31	7.31	11.5	1.5	5.7	6.71	11.5
A4	0.5	4.1	5.15	11.5	0.5	4.44	5.48	11.5	0.5	4.44	5.48	11.5	3	5.58	6.59	11.5	2	6.93	7.95	11.5
A5	1.5	4.67	5.68	11.5	0.5	5.24	6.26	11.5	0.5	4.75	5.79	11.5	3	6.22	7.23	11.5	1.5	6.64	7.68	11.5
ALTERNATIVES	**HUMAN HEALTH AND SAFETY (C6)**				**LOCAL ECONOMIC DEVELOPMENT (C7)**				**RECYCLABILITY (C8)**				**HUMAN SATISFACTION (C9)**				**PRACTICABILITY (C10)**			
A1	1.5	6.53	7.55	11.5	0.5	5.82	6.84	11.5	0.5	4.43	5.49	11.5	0.5	6.56	7.64	11.5	0.5	7.52	8.66	11.5
A2	1.5	5.72	6.73	11.5	0.5	6.44	7.47	11.5	0.5	4.67	5.7	11.5	0.5	6.53	7.62	11.5	0.5	7.38	8.52	11.5
A3	1.5	5.78	6.79	11.5	0.5	6.38	7.41	11.5	0.5	4.81	5.85	11.5	0.5	6.06	7.09	11.5	0.5	7.07	8.15	11.5
A4	1.5	6.14	7.15	11.5	0.5	6.16	7.18	11.5	0.5	4.24	5.29	11.5	0.5	5.09	6.12	11.5	0.5	5.88	6.91	11.5
A5	1.5	6.06	7.06	11.5	0.5	6.57	7.6	11.5	0.5	4.61	5.65	11.5	0.5	5.45	6.48	11.5	0.5	6.71	7.75	11.5

Table 6.9 Normalized fuzzy decision matrix for alternative and evaluation of factors

ALTERNATIVES	C1				C2				C3				C4				C5			
A1	0.33	0.07	0.06	0.04	0.17	0.07	0.06	0.04	1.00	0.09	0.07	0.04	0.50	0.19	0.17	0.13	0.33	0.07	0.06	0.04
A2	1.00	0.09	0.08	0.04	0.33	0.09	0.07	0.04	1.00	0.11	0.09	0.04	1.00	0.24	0.21	0.13	1.00	0.09	0.07	0.04
A3	0.33	0.10	0.08	0.04	0.33	0.09	0.07	0.04	1.00	0.11	0.09	0.04	1.00	0.24	0.21	0.13	0.33	0.09	0.07	0.04
A4	1.00	0.12	0.10	0.04	1.00	0.11	0.09	0.04	1.00	0.11	0.09	0.04	0.50	0.27	0.23	0.13	0.25	0.07	0.06	0.04
A5	0.33	0.11	0.09	0.04	1.00	0.10	0.08	0.04	1.00	0.11	0.09	0.04	0.50	0.24	0.21	0.13	0.33	0.08	0.07	0.04
ALTERNATIVES	**C6**				**C7**				**C8**				**C9**				**C10**			
A1	1.00	0.23	0.20	0.13	0.04	0.51	0.60	1.00	0.04	0.39	0.48	1.00	0.04	0.57	0.66	1.00	0.04	0.65	0.75	1.00
A2	1.00	0.26	0.22	0.13	0.04	0.56	0.65	1.00	0.04	0.41	0.50	1.00	0.04	0.57	0.66	1.00	0.04	0.64	0.74	1.00
A3	1.00	0.26	0.22	0.13	0.04	0.56	0.64	1.00	0.04	0.42	0.51	1.00	0.04	0.53	0.62	1.00	0.04	0.62	0.71	1.00
A4	1.00	0.24	0.21	0.13	0.04	0.54	0.62	1.00	0.04	0.37	0.46	1.00	0.04	0.44	0.53	1.00	0.04	0.51	0.60	1.00
A5	1.00	0.25	0.21	0.13	0.04	0.57	0.66	1.00	0.04	0.40	0.49	1.00	0.04	0.47	0.56	1.00	0.04	0.58	0.67	1.00

Table 6.10 Combined weighted matrix for evaluation of factors

Factor	C1				C2				C3				C4				C5			
COMBINED WEIGHT	1.647	1.830	2.105	2.105	1.013	1.249	1.418	1.553	0.270	0.333	0.378	0.414	1.428	1.587	1.825	1.825	0.496	0.814	0.924	1.158
	C6				**C7**				**C8**				**C9**				**C10**			
	0.113	0.146	0.165	0.198	0.029	0.058	0.067	0.088	0.044	0.080	0.092	0.113	0.542	0.798	0.919	1.084	1.626	2.005	2.276	2.493

Step 6: The normalized fuzzy weighted decision matrix is computed using Equation 6.16 and is represented in Table 6.11.

Step 7: The alternative distance to the ideal solution, the FPIS and FNIS are determined using Equation 6.17. The distances are calculated from the positive and negative fuzzy matrix using Equations (6.18, 6.19 & 6.20) and are shown in Table 6.12.

Step 8: Compute the Closeness Coefficient (CC_i) using Equation 6.21. Higher the CC_i value, better is the alternative preference towards sustainability. The preferential order of sustainable binder alternative is obtained as A2 > A3 > A1 > A4 > A5.

Though the ranking order is preferred to select the best alternative, the linguistic variables are chosen to generalize the proposed class of ranking and determine the deviation of selected alternative with respect to sub-intervals in the deviation limit (Table 6.13). The deviation of an alternative is determined by multiplying Closeness Coefficient (CC_i) value with the corresponding Rank (R_i) of an alternative (Equation 6.22).

$$D_i = CC_i \times R_i \quad \text{(Eq 6.22)}$$

Table 6.12 gives the distance from Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) and Ranks the ideal solution based on Closeness Coefficient (CC). The Deviation (D_i) of an alternative from the ideal solution is determined to setup a deviation limit range and generalize the acceptance status based on the number of alternatives. Table 6.13 shows the acceptance status of an alternative with respect to the proposed deviation limit range. Among the alternatives shown in Table 6.12, PPC-F is ranked first with the lowest Deviation of 0.549 from the ideal solution. Similarly, for all other material alternatives, the Deviation (D_i) is obtained from Equation 6.20. Based on the Deviation (D_i), different ranges are classified and specified with the acceptance status (Table 6.13). Lower the deviation, better is the ranking of material alternative. It is noticed that the material which is ranked first with a deviation of 0.549 belongs to Class I and is the most 'Accepted and preferred' alternative. Similarly, based on the deviation, the deviation limits, and classification, the priority of alternative material is ascertained (Table 6.13).

Table 6.11 Normalized fuzzy weighted matrix

C1					C2					C3					C4					C5				
A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
0.55	1.65	0.55	1.65	0.55	0.17	0.34	0.34	1.01	1.01	0.27	0.27	0.27	0.27	0.27	0.71	1.43	1.43	0.71	0.71	0.17	0.50	0.17	0.12	0.17
0.13	0.15	0.16	0.20	0.18	0.07	0.09	0.09	0.11	0.10	0.02	0.03	0.03	0.03	0.03	0.27	0.34	0.34	0.38	0.34	0.03	0.04	0.04	0.04	0.04
0.13	0.13	0.13	0.16	0.15	0.06	0.07	0.07	0.09	0.08	0.02	0.02	0.02	0.02	0.02	0.24	0.30	0.29	0.32	0.30	0.03	0.04	0.04	0.03	0.03
0.09	0.07	0.07	0.07	0.07	0.04	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01	0.01	0.19	0.19	0.19	0.19	0.19	0.02	0.02	0.02	0.02	0.02

C6					C7					C8					C9					C10				
A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
0.11	0.11	0.11	0.11	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.07	0.07	0.07	0.07	0.07
0.03	0.03	0.03	0.03	0.03	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.31	0.31	0.29	0.24	0.26	1.06	1.04	1.00	0.83	0.95
0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.36	0.36	0.33	0.29	0.31	1.22	1.20	1.15	0.98	1.10
0.01	0.01	0.01	0.01	0.01	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.54	0.54	0.54	0.54	0.54	1.63	1.63	1.63	1.63	1.63

Table 6.12: Distance from FPIS & FNIS and Closeness Coefficient(CC_i)

Alternatives	d*	d^-	CC_i	Ranking (R_i)	Deviation (D_i)
OPC (A1)	3.661	3.781	0.508	3	1.524
PPC-F (A2)	4.056	4.928	0.549	1	0.549
PPC-S (A3)	3.749	4.152	0.525	2	1.051
GP (A4)	4.413	4.526	0.506	4	2.025
CC (A5)	4.013	4.087	0.505	5	2.523

Table 6.13: Deviation limit and Classification

Deviation limit	Acceptance status	Class
$A_i \in [0.0,1.0)$	Accepted and Preferred	C I
$A_i \in [1.0, 2.0)$	Partially accepted with the condition	C II
$A_i \in [2.0,3.0)$	Least accepted with low risk	C III
$A_i \in [3.0,4.0)$	Least accepted with high risk	C IV
$A_i \in [4.0,5.0]$	Not recommended	C V

The proposed hybrid framework in this study integrates the Objective (Entropy) and Subjective (Fuzzy set theory) weights and ranks the alternatives using FTOPSIS. The unbiased Decision Makers (DM's) preferences which involve vagueness and uncertainty has been resolved using linguistic variables assigned with trapezoidal fuzzy numbers. The method expels the fuzziness, vagueness, and imprecision in evaluating the performance rating and weights using intrinsic fuzzy logic concept.

6.6 Method II : Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) method for evaluating factor weights is a simple and most popular method. It is practical to determine the weights of factors and alternatives. This method includes the subjectivity of the problem, where the problem is decomposed into a number of hierarchy levels to analyze them independently (Saaty, 2008). AHP is a simple and lucid way to obtain the interrelationship between various factors and alternatives using pairwise comparison which is apt for the present study. Selection of on optimal building material is considered as a multi-attribute decision problem, considering various sustainable factors, and alternatives as a decision problem (Chen et al., 2010; Khoshnava et al., 2018).

The following steps are involved in determining the relative weights of factors.

Step 1- Decompose the problem into a hierarchy of factors and alternative.

Step 2 - Compose the pairwise comparison matrix for each alternative with respect to a factor. Consider the matrix A which is m x m real matrix, where 'm' stands for a number of evaluation factors, each entry a_{ij} in matrix A shows the importance of i^{th} factor to j^{th} factor.

$$\begin{matrix} & C1 & C2 & \ldots\ldots\ldots & Cm \end{matrix}$$

$$\mathbf{A} = [a_{ij}] = \begin{vmatrix} 1 & a_{12} & \cdots & a_{1m} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{1m}} & \frac{1}{a_{2m}} & \ldots & 1 \end{vmatrix}$$

If $a_{ij} > 1$ ……….then i^{th} factor is more important than j^{th} factor

If $a_{ij} < 1$ ……….then i^{th} factor is less important than j^{th} factor

If $a_{ij}=1$ …………then two factors are equal $a_{ij} \times a_{ji} = 1$

Step 3 – Using Equation 6.23, determine the normalized matrix A_{ij} from the above-obtained matrix by aggregating the values in each column and then divide each element of the matrix by its column total.

$$A_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{1j}} \qquad \text{(Eq 6.23)}$$

Using Equation 6.24, it can be seen that all the columns in the normalized pairwise comparison matrix have a sum of 1. Take overall row average which will determine the relative weight.

$$w_j = \sum_{i=1}^{m} \frac{a_{ij}}{m} \qquad \text{(Eq 6.24)}$$

Step 5 – Check for Consistency Index (CI) < 0.10, the ratio is designed in such a way that values of the ratio exceeding 0.10 are indicative of inconsistent judgments using Equation (6.25 & 6.26)

Consistency Index (CI) $$CI = \frac{\lambda_{max} - n}{n - 1}$$ (Eq 6.25)

Consistency Ratio (CR) $$CR = \frac{CI}{RI}$$ (Eq 6.26)

'RI' represents the Random Index value; λ_{max} represents the maximum Eigen value; 'n' is the size of the matrix.

Considering the four sustainable SEET indicators (Social, Environmental, Economic, and Technological) and 10 sustainable factors, the sustainable material performance is assessed by considering multi-dimensional factors (Reddy, Kumar, & Raj, 2019a). The scientific evidence proposes that the assessment of significant sustainable performance factor can be performed by a consensus-based process which best suits the comprehensive analysis (Reddy A.S, Kumar P. R, & Raj P. A, 2018). The proposed methodology as shown in Fig 6.5 has been developed based on how sustainability in construction has to be achieved, keeping in view the four dimensions (SEET) and sustainable factors.

In the present study, a questionnaire survey collected 54 responses from Academicians, Designers, Architects, Consultants, Clients, Contractors, and Others to analyze their significance towards material sustainability on a seven point Likert scale (Appendix D). The data extracted was observed to be consistent using Cronbach's alpha coefficient. They are then processed, analyzed and interpreted using statistical techniques to extract the required information. This information is then analyzed using Analytical Hierarchy Process a pairwise comparison Multi-Criteria Decision-Making (MCDM) method to establish interrelationship among material alternatives with respect to each sustainable factors. The study has proposed a conversion scale from Likert scale to AHP Saaty's scale to get quick response and is as shown in Table 6.14.

Table 6.14 Proposed converted scale from Likert scale (1 – 7) to Saaty's scale (1 – 9)

Saaty's Scale		**Converted Scale**	
Relative Importance	**Definition**	**Comparative scale**	**Importance/Preference**
1	Of equal importance	7-7	Difference of values =0
3	Slightly more value	6-7	Difference of values =1
5	Essential or strong value	5-7	Difference of values =2
7	Very strong value	3-7; 4-7	Difference of values =3 or 4
9	Extreme value	1-7; 2-7	Difference of values =5 or 6

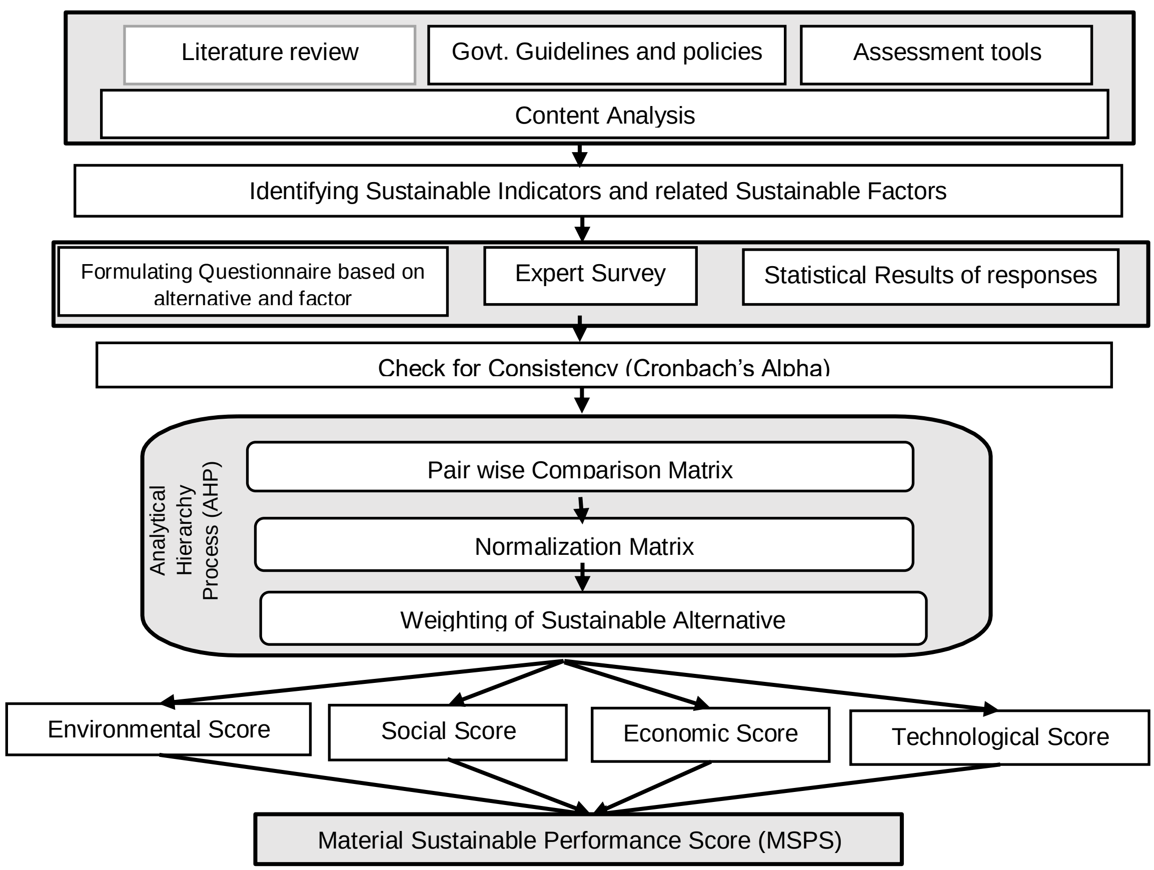


Fig 6.5 Framework to Develop Material Sustainable Performance Score (MSPS)

6.6.1 Illustration of example

An example is illustrated for the approach followed in the AHP method using the converted scale with respect to one of the factors. The significance of an alternative with respect to say Global Warming Potential (GWP) emission by one of the respondents is shown in Table 6.15. Likewise, 10 pairwise comparison matrices with 5 x 5 size are formulated for each respondent (i.e., 54 x 10) to determine the relative weight of material alternatives as shown in Tables (6.15 - 6.17).

Table 6.15 Response of Experts

Binder Material alternative	Ordinary Portland Cement	PPC Fly ash based	PPC Slag based	Geopolymer	Composite Cement
	OPC	**PPC-F**	**PPC-S**	**GP**	**CC**
Response	1	3	4	5	4

The relative importance of alternatives (OPC and PPC-F) with respect to GWP emissions is given as '1' and '3' respectively (Table 6.14). Therefore, the difference in the relative importance of OPC and PPC-F is 2. From Table 6.2, the corresponding relative importance for the difference value of '2' is observed to be '5'. Since the alternatives, OPC and PPC-F are compared based on GHG indicator and the alternative PPC-F rating is higher than the OPC rating, the pairwise comparison is considered as reciprocal (i.e., 1/5 = 0.20). Similarly, the pairwise comparison matrix is developed for all the material alternatives.

Table 6.16 Pairwise Comparison Matrix

Alternatives	**OPC**	**PPC-F**	**PPC-S**	**GP**	**CC**
OPC	1.00	0.20*	0.20*	0.14*	0.20*
PPC-F	5.00	1.00	0.33*	0.20*	0.33*
PPC-S	5.00	3.00	1.00	0.33*	1.00
GP	7.00	5.00	3.00	1.00	1.00
CC	5.00	3.00	1.00	1.00	1.00
Sum	**23.00**	**12.20**	**5.53**	**2.68**	**3.53**

*Reciprocal values if j > i

Table 6.17 Normalization Matrix

Alternatives	OPC	PPC-F	PPC-S	GP	CC	Average	W%
OPC	0.04	0.02	0.04	0.05	0.06	0.04	**4.12%**
PPC-F	0.22	0.08	0.06	0.07	0.09	0.11	**10.58%**
PPC-S	0.22	0.25	0.18	0.12	0.29	0.21	**21.08%**
GP	0.30	0.41	0.54	0.37	0.28	0.38	**38.28%**
CC	0.22	0.25	0.18	0.37	0.28	0.26	**26.03%**
Sum	1.00	1.00	1.00	1.00	1.00		

'RI', the Random Index value, is the average CI for a large number of randomly generated matrices for the same order; λ_{max} represents the maximum Eigen value; 'n' is the size of the matrix (n = 5).

Maximum Eigen value is calculated from Tables (6.16 & 6.17)

λ_{max} = {[(23*4.12) + (12.2*10.58) + (5.53*21.08) + (2.67*38.28) + (3.533*26.02)]/100} = 5.34.

From Equation 6.25, the Consistency Index (CI) was found to be 0.085. Based on the size of the matrix, the RI value is found to be 1.12 (Forman & Peniwati 1998). From Equation 6.26 the Consistency Ratio (CR) = 0.075< 0.10. Hence, the data is reliable and consistent. Finally, the relative weights of factors to an alternative are obtained by pooling along the rows.

Step 6 – The average AHP relative weight of an alternative for all the respondents with respect to each factor (see Table 6.18) are calculated.

Table 6.18 Relative weights of alternative with respect to sustainable factors

FACTORS	OPC	PPC-F	PPC-S	GP	CC
F1	0.09	0.17	0.18	0.31	0.25
F2	0.1	0.16	0.16	0.34	0.24
F3	0.13	0.21	0.22	0.25	0.19
F4	0.1	0.2	0.19	0.3	0.21
F5	0.13	0.27	0.26	0.15	0.19
F6	0.15	0.23	0.22	0.2	0.2
F7	0.17	0.21	0.19	0.2	0.23
F8	0.2	0.2	0.22	0.18	0.2
F9	0.25	0.25	0.2	0.15	0.15
F10	0.24	0.24	0.2	0.14	0.18

Step 7 – Obtain the final Material Sustainable Performance Score (MSPS) by aggregating each alternative relative weight with respect to sustainable factor and indicator using Table 6.2. To select a sustainable alternative material, the AHP relative weighted score is calculated for Environmental, Economic, Social and Technological indicators and as shown in Figs 6.7, 6.8 and 6.9 respectively. The higher the sustainable material score, higher is the material sustainability. Considering the environmental parameter, the alternative geopolymer based concrete has secured the highest score of 1.53 (Fig 6.6). Similarly, considering economic parameter, PPC fly ash based concrete was rated high at 1.12 (Fig 6.7). In the social parameter, PPC fly ash based concrete has rated high as 0.69 (Fig 6.8). Similarly, considering technological parameter, PPC fly ash based concrete has secured the highest score of 0.44 (Fig 6.9).

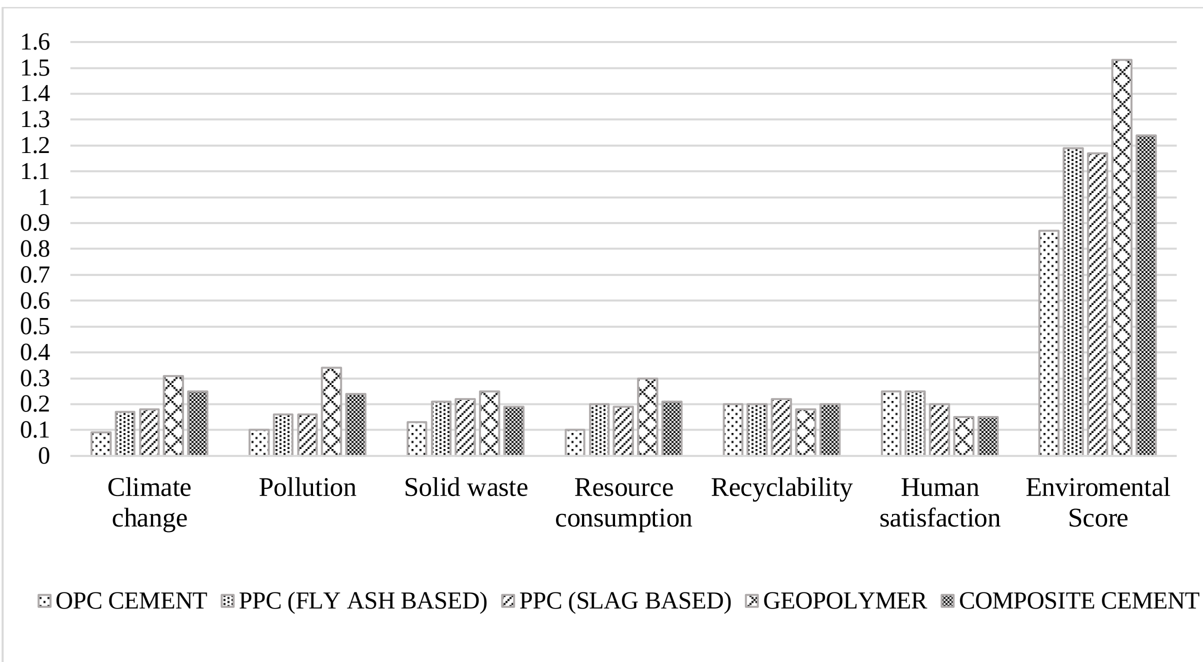


Fig. 6.6 Relative scores of alternatives with respect to Environmental Indicator

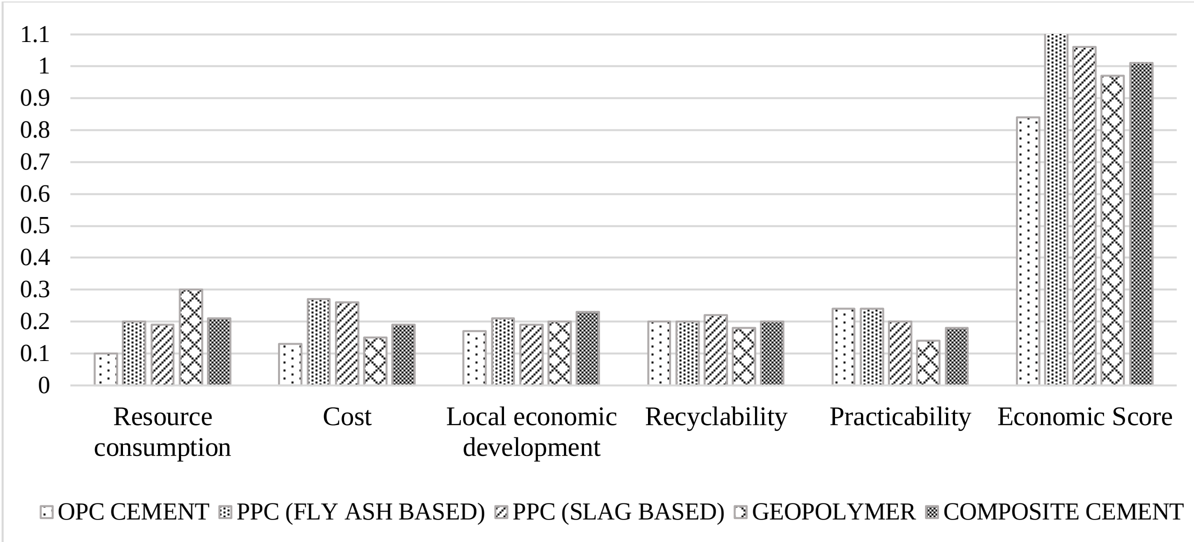


Fig. 6.7 Relative scores of alternatives with respect to Economic Indicator

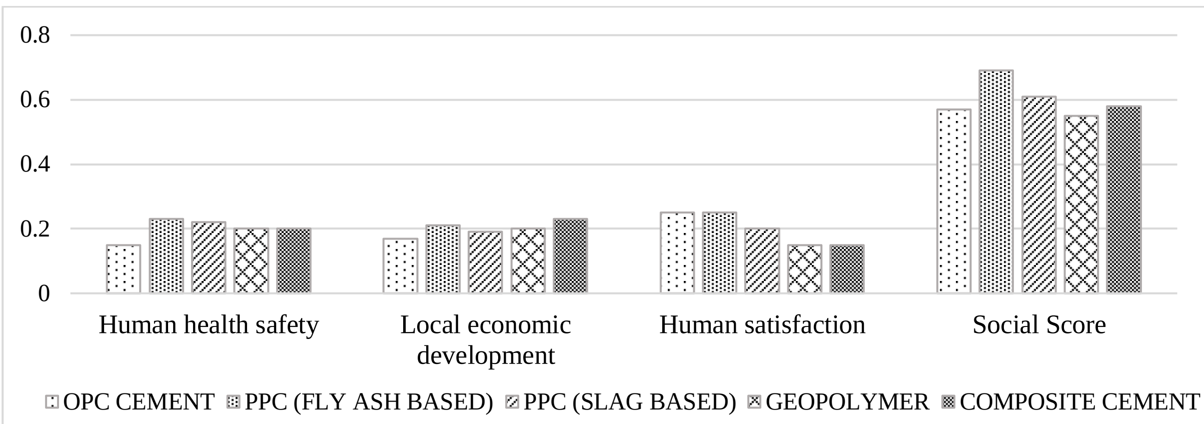


Fig. 6.8. Relative scores of alternatives with respect to Social Indicator

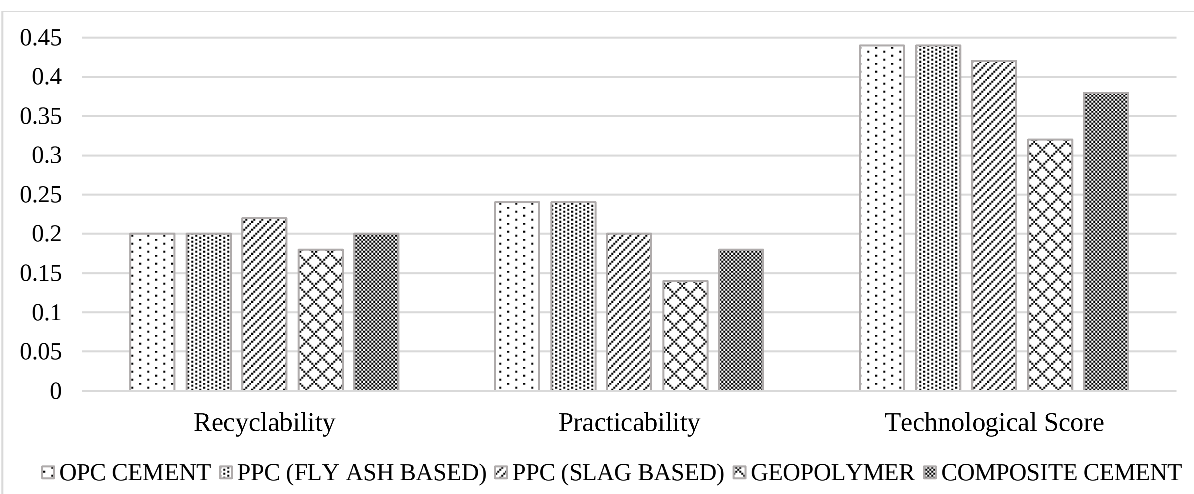


Fig. 6.9 Relative scores of alternatives with respect to Technological Indicator

The SEET sustainable indicator weights may vary with various constraints like location and regional context, climate conditions, culture, geographical conditions and awareness. In the present work, the relative weights of the indicators environmental, economic, social and technological are obtained based on the experts opinion (Academicians, Designers, Consultants, Architects, Engineers and other stakeholder from the construction industry) and analysed using AHP approach(Reddy A S, P. R Kumar & Anand Raj P, 2018a). The values are respectively 0.4, 0.3, 0.12 and 0.18. To obtain the overall MSPS the weighted average for material alternatives is calculated and the normalized scores for various material alternatives is shown in Table 6.19.

Ordinary Portland cement = (0.4x0.87) + (0.3x0.84) + (0.12x0.57) + (0.18x0.41) = 0.71

Pozzolona Fly Ash Based = (0.4x1.19) + (0.3x1.12) + (0.12x0.69) + (0.18x0.44) = 0.97

Pozzolona Slag Based = (0.4x1.17) + (0.3x1.06) + (0.12x0.61) + (0.18x0.42) = 0.94

Geopolymer = (0.4x1.53) + (0.3x0.97) + (0.12x0.55) + (0.18x0.32) = 1.03

Composite Cement = (0.4x1.24) + (0.3x1.01) + (0.12x0.58) + (0.18x0.38) = 0.92

Table 6.19 Normalized scores for material alternatives

Material Alternatives	OPC Cement	PPC (Fly ash Based)	PPC (Slag Based)	Geopolymer	Composite Cement
Material Sustainable Performance Score [MSPS]	0.34	0.47	0.45	0.50	0.42
Selection Priority (Ranking)	**5**	**2**	**3**	**1**	**4**

6.7. Method III: Sustainable Material Performance Index (SMPI)

This method is simple, robust and involves a conceptual framework to assess the sustainable performance of construction materials. This involves integrating three ideas: Sustainable factors and SEET indicator, Material life cycle thinking and developing Sustainable Material Performance Indices (SMPI) as shown in Fig 6.10. The method utilizes the concepts of AHP and Relative Importance Index (RII) to measure the material performance by integrating sustainable indicators, factors influencing the material performance and three phases of the material lifecycle.

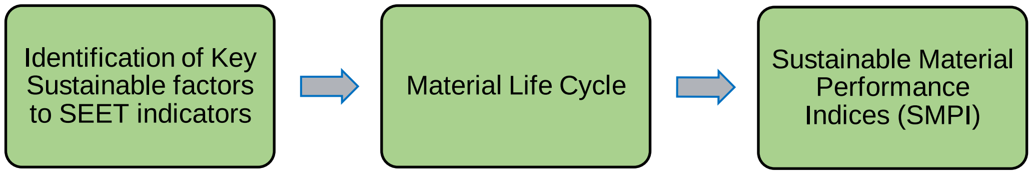


Fig 6.10 Stages of approach for developing material performance indices

The various life cycle stages (Preconstruction, Construction, and Post Construction) are considered in the study to observe the material performance with respect to sustainable factors. Each sustainable factor is integrated with three life cycle phase to evaluate the material indices Fig 6.11.

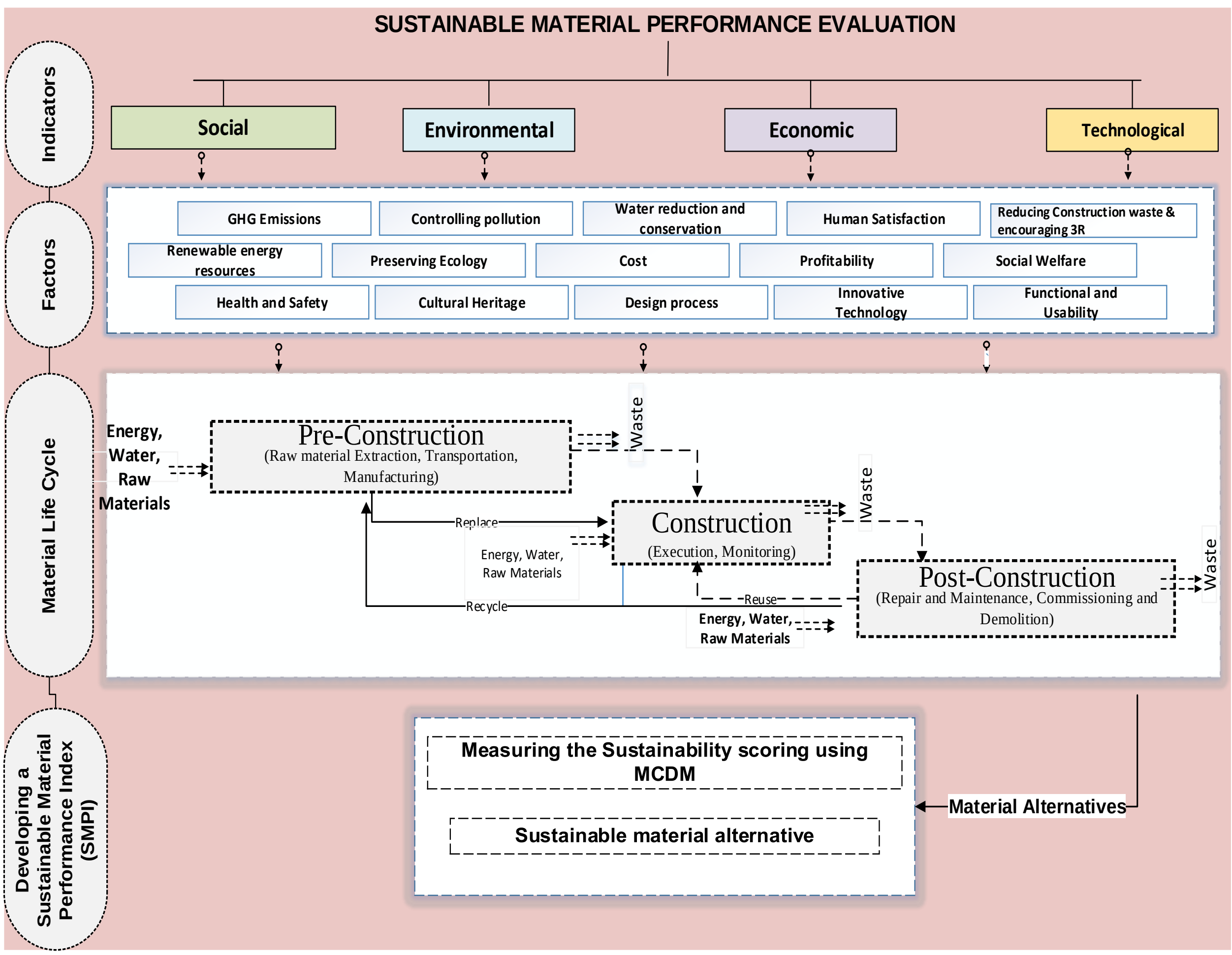


Fig 6.11 Life Cycle Stages

The methodology can thus be utilized achieving sustainable performance without the need for material inventory data. The detailed approach for developing a Sustainable Material Performance Index (SMPI) is shown in Fig 6.12.

The quantitative and qualitative approach Analytical Hierarchy process (AHP) is decomposed into a number of hierarchy levels to analyze them independently (Saaty, 2008). AHP is a simple and lucid way to obtain the interrelationship between various factors and alternatives using pairwise comparison which is apt for the present study. While the Relative Importance Index (RII) is utilized to observe the significance of each life cycle stage (Pre Construction, Construction, and Post Construction) with respect to sustainable factors.

By integrating the relative weight of alternative with respect to factors obtained from AHP method and the relative weight of life cycle stage with respect to factors obtained from RII method, the study facilitates to prioritize the material alternatives in each life cycle phase, each sustainable indicator (SEET) and also the overall sustainable performance.

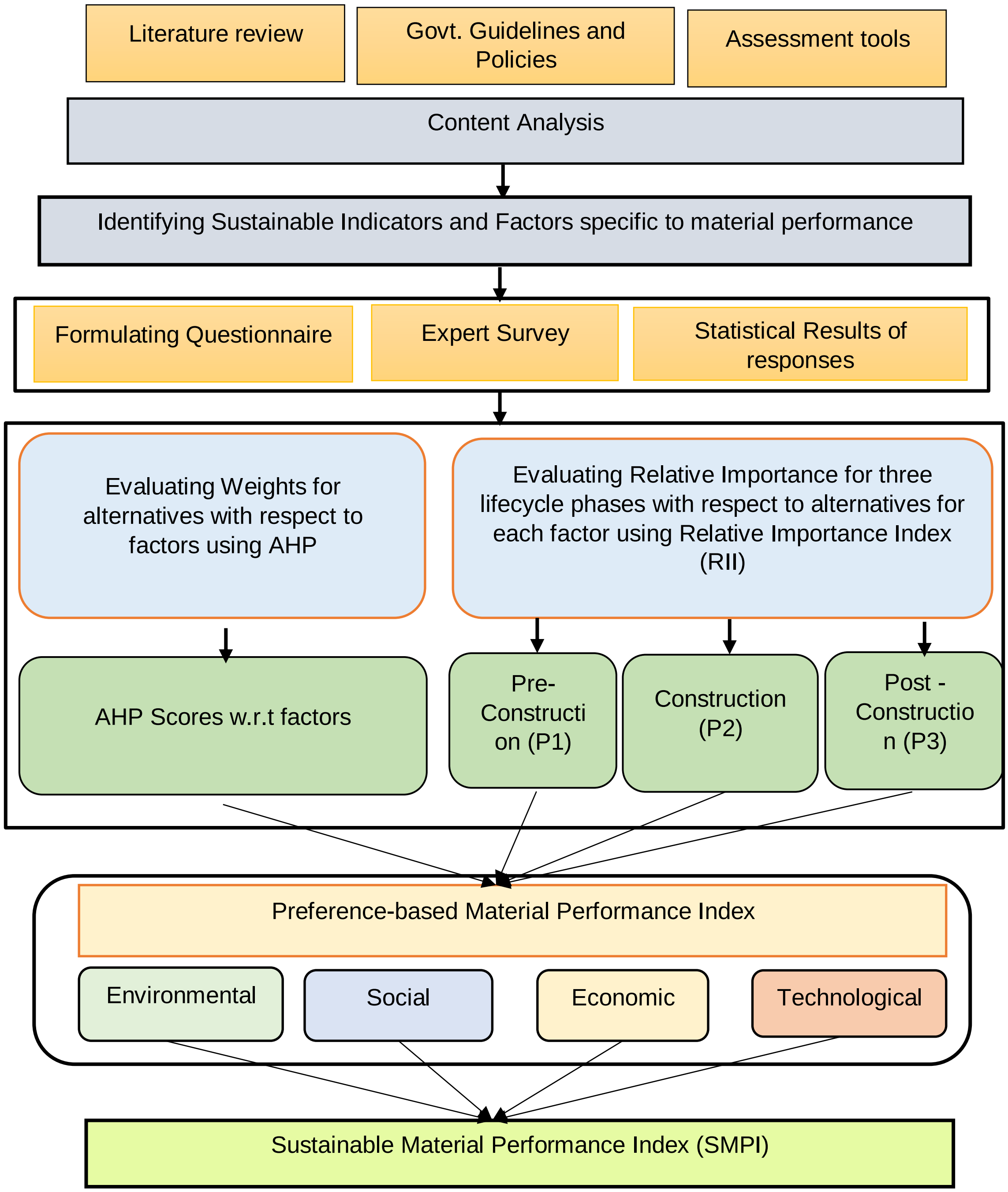


Fig. 6.12 Framework for Evaluating Sustainable Material Performance Index (SMPI)

6.7.1 Importance of Lifecycle Phases

It is vital to understand the material performance in various phases of life cycle and it is also complex to analyze the importance of each phase for a particular material and sustainable factor. Relative Importance Index (RII) is a statistical approach adopted to determine the relative weight of variables using Equation 6.27. The questionnaire survey consists of three phases of life cycle and five material alternatives for a binder with respect to each of the 10 sustainable factors (Table 6.20). Based on the questionnaire and the response obtained from eight experts from various backgrounds of construction industry, the Relative Importance Index of three phases of lifecycle is determined. Higher the value of RII, greater will be the importance of the lifecycle phase with respect to sustainable indicators (Fig 6.13).

Table 6.20 Sample Questionnaire comprising life cycle phases and material alternatives

***For factor (x_j); Binder Material Alternatives* (A_i)**	**Pre-Construction (P1)**							**Construction (P2)**							**Post-Construction (P3)**						
	1	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	VL	**L**	**BM**	**M**	**AM**	**H**	**VH**	**VL**	**L**	**BM**	**M**	**AM**	**H**	**VH**	**VL**	**L**	**BM**	**M**	**AM**	**H**	**VH**
Alternative 1																					
Alternative 2																					
Alternative 3																					
Alternative 4																					
Alternative 5																					

VL- Very Low; L- Low; BM- Below Moderate; M- Moderate; Am- Above Moderate; H- High; VH- Very High

$$RII_{ij}^{k} = \frac{\sum_{r=1}^{N} w_{ijk}^{r}}{w_{\max} \times N} \qquad \text{(Eq 6.27)}$$

(i = 1,…to…n, number of alternatives; j = number of factors; k represents lifecycle phase)

w_{ij} is the weight given by the respondent ‘r’ to each alternative with respect to each factor (between scale 1 and 7), w_{max} is the highest weight (in this case 7), N is the number of respondents. A term, Relative Importance Percentage (RIP) is introduced to understand the significance of each phase and to observe the performance of a material passing through it. The Relative Importance for three phases of the life cycle (Pre-Construction, Construction, Post-Construction) was evaluated using Equations (6.28 & 6.29) as shown in Fig 6.14.

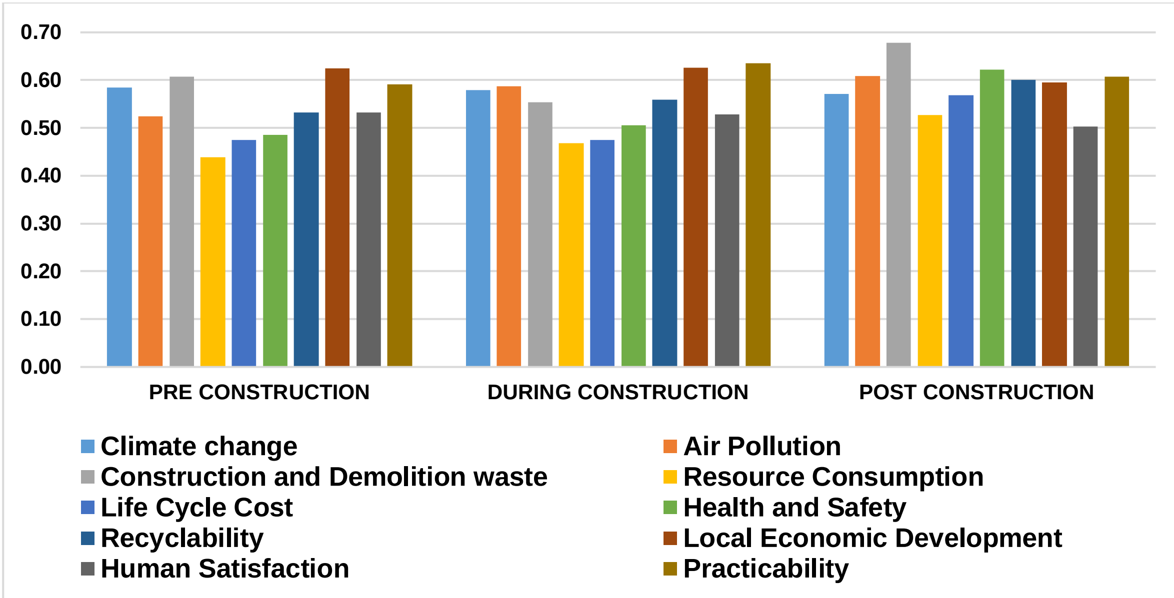


Fig. 6.13 Average RII of each lifecycle phase with respect to sustainable indicators

$$RII_j^k = \frac{\sum_{i=1}^{n} RII_{ij}^k}{n}$$ ('n' represents number of alternatives) (Eq 6.28)

$$RIP_j^k = \frac{RII_j^k}{\sum_{k=1}^{k} RII_j^k} \times 100$$ (i = number of alternatives 1 to 5; k= no of lifecycle phases 1 to z) (Eq 6.29)

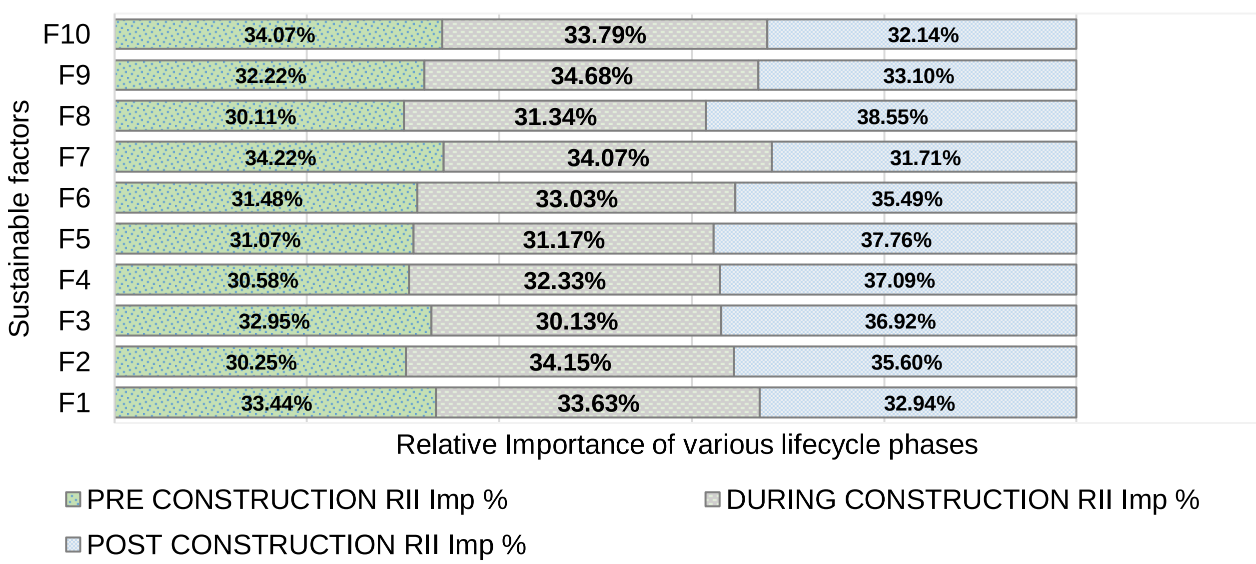


Fig 6.14 Relative Importance Percentage (RIP) of three lifecycle phases

6.7.2 Sustainable Material Performance Index (SMPI)

The second questionnaire survey has been designed considering seven point Likert scale, to evaluate the material performance with respect to sustainable factors. Keeping in view, the material lifecycle thinking, the data is obtained from the respondents. Here '1' represents less important whereas, '7' represents high importance (Appendix D). In other words, the higher the rate of importance, better is the sustainability. Since the questionnaire survey involves in-depth understanding of the proposed alternatives, the data has been collected from technically strong selected expert's viz., Academicians, Designers, Architects, Contractors, Engineers, Consultants among others (Fig 6.15) in the Indian construction sector. The study utilized modified scale converting the '7' point Likert scale to 9 point Saaty's scale for getting the responses (Table 6.3).

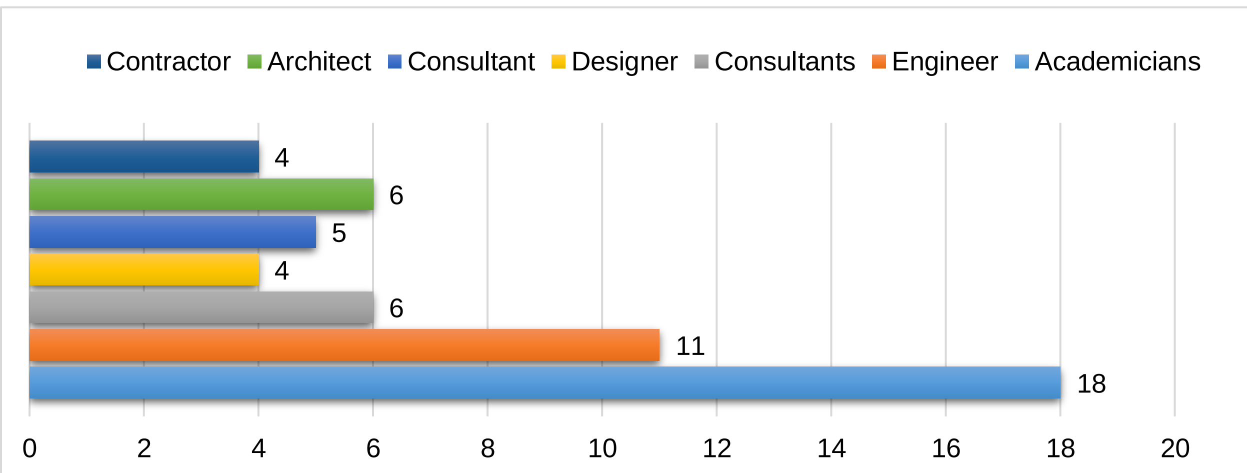


Fig. 6.15 Respondents and their related expertise

In order to identify the relative importance and interdependency of alternative materials with respect to each of the sustainable indicators, a pairwise comparison based on Analytical Hierarchy Process (AHP) has been performed.

The relative weight of the material is calculated based on the following steps

Step 1- Calculate importance of the alternative over each factor on the Likert scale 1 -7.

Step 2- Convert the Likert scale value to Saaty's scale (Table 6.3). If responses are given for three phases of life cycle take the average of them).

Step 3- Calculate the relative weights of alternatives using pairwise comparison (individual decision matrix).

Step 4- Normalize the matrix.

Step 5- Check for internal consistency using consistency index and consistency ratio of the pairwise matrix.

Step 6- Repeat the steps 1-5 for each decision maker's response.

Step 7- Average all the individual decision matrices to get the average aggregated decision matrix with respect to alternatives and factors using Equation 6.30 (Table 6.21).

$$C_{ij} = \frac{\sum_{r=1}^{n} x_{ij}^{r}}{n} \qquad \text{(Eq 6.30)}$$

Table 6.21 Average aggregated decision matrix of Binder material for various factors

Factors	OPC CEMENT	PPC (FLY ASH BASED)	PPC (SLAG BASED)	GEOPOLYMER	COMPOSITE CEMENT
Climate change	0.09	0.17	0.18	0.31	0.25
Pollution	0.10	0.16	0.16	0.34	0.24
Solid waste	0.13	0.21	0.22	0.25	0.19
Resource consumption	0.10	0.21	0.19	0.30	0.21
Cost	0.13	0.27	0.26	0.15	0.19
Human health safety	0.15	0.23	0.22	0.21	0.20
Local economic Development	0.17	0.20	0.19	0.20	0.23
Recyclability	0.17	0.20	0.22	0.18	0.20
Human satisfaction	0.25	0.25	0.21	0.15	0.15
Practicability	0.24	0.24	0.20	0.14	0.18

x_{ij} represents the relative AHP weight given by individual respondents 'r'. C_{ij} represents the average of relative AHP scores of i^{th} alternative corresponding to the j^{th} factor.

Step 8- With respect to Table 6.2, the consolidated average aggregated decision matrices are evaluated and are as shown in Tables (6.22 – 6.25) for the four sustainable indicators (SEET).

Table 6.22 Average Aggregated decision matrix (Environmental indicator)

Factors	**OPC CEMENT**	**PPC (FLY ASH BASED)**	**PPC (SLAG BASED)**	**GEOPOLYMER**	**COMPOSITE CEMENT**
Climate change	0.09	0.17	0.18	0.31	0.25
Pollution	0.11	0.16	0.16	0.34	0.24
Solid waste	0.13	0.20	0.22	0.25	0.19
Resource consumption	0.10	0.21	0.19	0.30	0.21
Recyclability	0.17	0.20	0.22	0.24	0.20
Human satisfaction	0.25	0.25	0.20	0.15	0.15
FINAL SCORE	**0.85**	**1.19**	**1.17**	**1.59**	**1.24**

Table 6.23 Average Aggregated decision matrix (Economic indicator)

Factors	OPC CEMENT	PPC (FLY ASH BASED)	PPC (SLAG BASED)	GEOPOLYMER	COMPOSITE CEMENT
Resource consumption	0.10	0.21	0.19	0.30	0.21
Cost	0.13	0.27	0.26	0.15	0.19
Local economic development	0.17	0.20	0.19	0.20	0.23
Recyclability	0.17	0.21	0.22	0.24	0.20
Practicability	0.24	0.24	0.20	0.23	0.18
FINAL SCORE	**0.81**	**1.13**	**1.06**	**1.12**	**1.01**

Table 6.24 Average Aggregated decision matrix (Social indicator)

Factors	**OPC CEMENT**	**PPC (FLY ASH BASED)**	**PPC (SLAG BASED)**	**GEOPOLYMER**	**COMPOSITE CEMENT**
Human health safety	0.15	0.23	0.22	0.21	0.20
Local economic development	0.17	0.20	0.19	0.20	0.23
Human satisfaction	0.25	0.25	0.20	0.15	0.15
FINAL SCORE	**0.57**	**0.69**	**0.61**	**0.56**	**0.58**

Table 6.25 Average Aggregated decision matrix (Technological indicator)

Factors	**OPC CEMENT**	**PPC (FLY ASH BASED)**	**PPC (SLAG BASED)**	**GEOPOLYMER**	**COMPOSITE CEMENT**
Recyclability	0.17	0.20	0.22	0.18	0.20
Practicability	0.24	0.24	0.20	0.14	0.18
FINAL SCORE	**0.41**	**0.44**	**0.42**	**0.47**	**0.38**

Step 9- The resultant interrelated matrices with respect to AHP score of the material and relative weight of the three phases of the lifecycle is utilized to develop the Sustainable

Material Performance Indices (SMPI) using Equation 6.31. They are then ranked based on SMPI values (Fig 6.16) and are represented in Table 6.26.

$$SMPI_{ij}^{k} = C_{ij} \times RII_{ij}^{k} \qquad \text{(Eq.6.31)}$$

RII_{ij} represents the relative importance index weight of i^{th} material and j^{th} factor with respect to the k^{th} lifecycle phase.

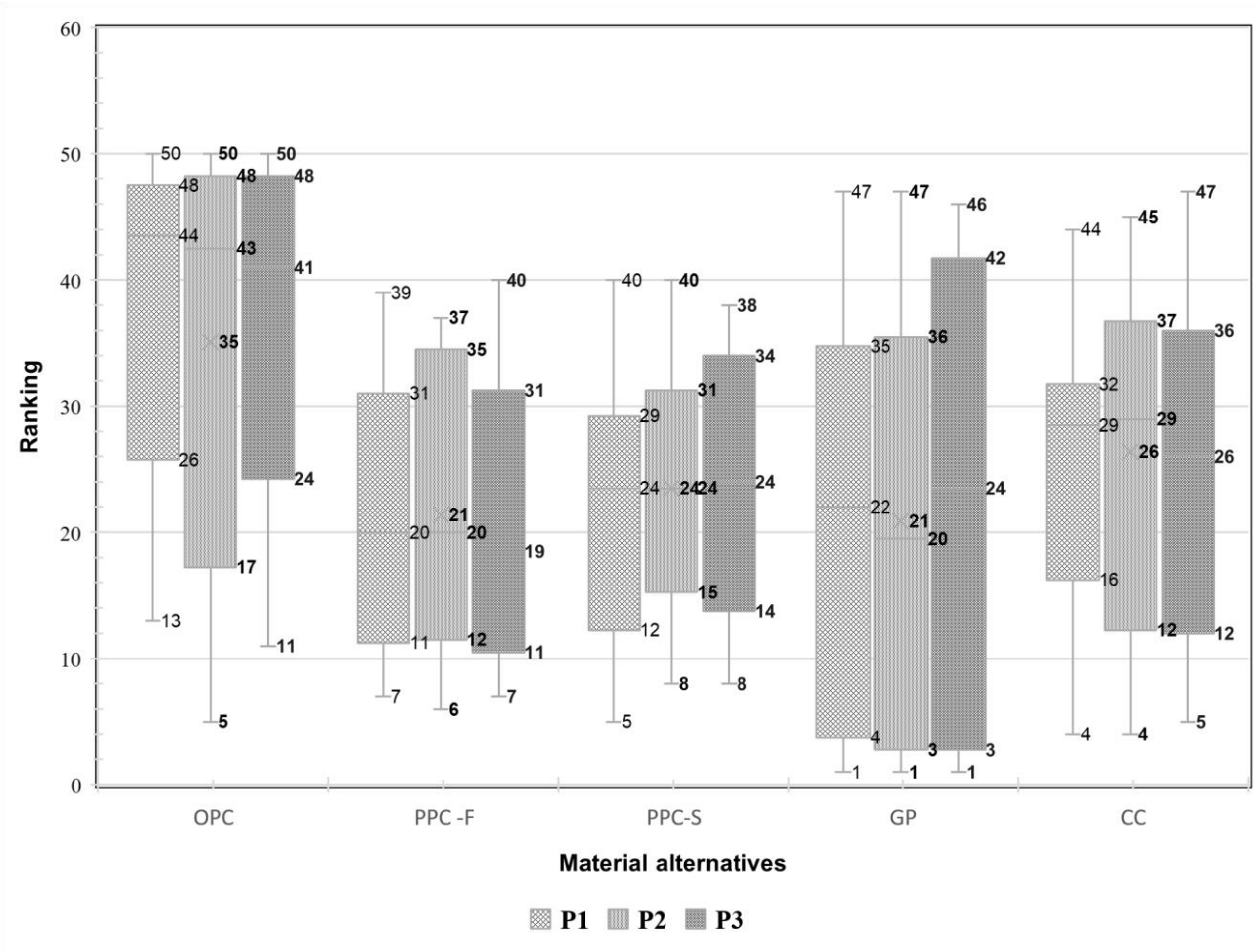


Fig 6.16 Ranking of binder material alternatives in the three phases of the lifecycle

Table 6.26 SMPI and RII for three phases of the lifecycle

Indicator	Alternative	Alternate Relative Weight	Pre-Construction (P1)				Construction (P2)				Post-Construction (P3)			
			RII	SMPI	Category Rank	Overall Rank	RII	SMPI	Category Rank	Overall Rank	RII	SMPI	Category Rank	Overall Rank
Climatic Change	**OPC**	0.09	0.36	0.032	5	**50**	0.42	0.038	5	**50**	0.38	0.034	5	**50**
	PPC -F	0.17	0.56	0.096	4	**34**	0.54	0.091	4	**34**	0.53	0.090	4	**42**
	PPC-S	0.18	0.57	0.103	3	**30**	0.55	0.100	3	**31**	0.56	0.101	3	**34**
	GP	0.31	0.80	0.249	1	**01**	0.73	0.227	1	**2**	0.73	0.227	1	**02**
	CC	0.25	0.63	0.156	2	**05**	0.65	0.163	2	**5**	0.66	0.165	2	**5**
Pollution	**OPC**	0.1	0.37	0.037	5	**48**	0.48	0.048	5	**48**	0.51	0.051	5	**49**
	PPC -F	0.16	0.50	0.080	3	**39**	0.55	0.089	3	**36**	0.61	0.097	3	**36**
	PPC-S	0.16	0.49	0.079	4	**40**	0.54	0.086	4	**38**	0.57	0.091	4	**40**
	GP	0.34	0.69	0.234	1	**02**	0.74	0.252	1	**1**	0.70	0.237	1	**01**
	CC	0.24	0.58	0.139	2	**15**	0.63	0.150	2	**9**	0.66	0.159	2	**6**
Construction & Demolition Waste	**OPC**	0.13	0.54	0.070	5	**45**	0.55	0.072	5	**44**	0.64	0.084	5	**43**
	PPC -F	0.21	0.55	0.116	4	**02**	0.54	0.113	3	**25**	0.68	0.143	3	**15**
	PPC-S	0.22	0.64	0.141	2	**13**	0.55	0.122	2	**20**	0.68	0.149	2	**11**
	GP	0.25	0.66	0.165	1	**03**	0.57	0.143	1	**12**	0.70	0.174	1	**03**
	CC	0.19	0.64	0.122	3	**19**	0.55	0.105	4	**29**	0.70	0.132	4	**20**
Resource Consumption	**OPC**	0.1	0.35	0.035	5	**49**	0.39	0.039	5	**49**	0.56	0.056	5	**48**
	PPC -F	0.2	0.43	0.087	3	**36**	0.43	0.087	3	**37**	0.53	0.106	2	**31**
	PPC-S	0.19	0.45	0.085	4	**38**	0.42	0.080	4	**40**	0.49	0.094	4	**39**
	GP	0.3	0.50	0.150	1	**08**	0.66	0.198	1	**03**	0.55	0.166	1	**04**
	CC	0.21	0.46	0.098	2	**31**	0.43	0.090	2	**35**	0.50	0.105	3	**33**
Life cycle Cost	**OPC**	0.13	0.46	0.060	4	**46**	0.52	0.067	4	**46**	0.57	0.074	5	**45**
	PPC -F	0.27	0.55	0.149	2	**10**	0.52	0.140	2	**13**	0.57	0.154	1	**07**
	PPC-S	0.26	0.59	0.153	1	**07**	0.55	0.144	1	**10**	0.59	0.153	2	**08**
	GP	0.15	0.39	0.059	5	**47**	0.38	0.056	5	**47**	0.55	0.083	4	**44**
	CC	0.19	0.38	0.071	3	**44**	0.41	0.078	3	**42**	0.55	0.105	3	**32**
Health & Safety	**OPC**	0.15	0.48	0.072	5	**42**	0.53	0.079	5	**41**	0.61	0.091	5	**41**
	PPC -F	0.23	0.50	0.115	1	**23**	0.52	0.119	1	**22**	0.64	0.148	1	**12**
	PPC-S	0.22	0.52	0.114	2	**24**	0.52	0.114	2	**24**	0.64	0.141	2	**17**
	GP	0.2	0.45	0.089	4	**35**	0.48	0.096	4	**33**	0.60	0.120	4	**28**
	CC	0.2	0.48	0.096	3	**33**	0.48	0.096	3	**32**	0.62	0.123	3	**24**
Local Economic Development	**OPC**	0.17	0.51	0.087	5	**37**	0.50	0.085	5	**39**	0.57	0.097	5	**37**
	PPC -F	0.21	0.53	0.111	2	**26**	0.57	0.120	2	**21**	0.59	0.124	2	**23**
	PPC-S	0.19	0.56	0.107	4	**28**	0.58	0.110	4	**27**	0.62	0.117	4	**29**
	GP	0.2	0.54	0.107	3	**27**	0.57	0.114	3	**23**	0.61	0.121	3	**25**
	CC	0.23	0.53	0.121	1	**20**	0.57	0.131	1	**17**	0.62	0.142	1	**16**
Recyclability & Reusability	**OPC**	0.17	0.57	0.097	5	**32**	0.60	0.120	5	**30**	0.56	0.096	5	**38**
	PPC -F	0.20	0.62	0.123	4	**18**	0.64	0.129	3	**18**	0.60	0.120	4	**27**
	PPC-S	0.22	0.65	0.143	3	**11**	0.63	0.139	1	**15**	0.60	0.132	2	**21**
	GP	0.24	0.67	0.161	1	**04**	0.69	0.165	4	**04**	0.63	0.150	1	**09**
	CC	0.22	0.71	0.155	2	**06**	0.63	0.139	1	**14**	0.59	0.130	3	**22**
Human Satisfaction	**OPC**	0.24	0.57	0.139	2	**16**	0.59	0.143	1	**11**	0.57	0.139	1	**18**
	PPC -F	0.25	0.57	0.143	1	**12**	0.57	0.143	2	**12**	0.54	0.134	2	**19**
	PPC-S	0.21	0.55	0.116	3	**21**	0.54	0.113	3	**25**	0.54	0.113	3	**30**
	GP	0.15	0.48	0.073	4	**41**	0.48	0.073	4	**43**	0.45	0.067	4	**46**
	CC	0.15	0.48	0.072	5	**42**	0.46	0.070	5	**45**	0.43	0.064	5	**47**
Practicability & Feasibility	**OPC**	0.24	0.56	0.135	3	**17**	0.64	0.154	1	**6**	0.62	0.148	2	**12**
	PPC -F	0.24	0.59	0.141	2	**13**	0.63	0.152	2	**7**	0.63	0.150	1	**09**
	PPC-S	0.20	0.56	0.113	4	**25**	0.63	0.127	3	**19**	0.61	0.121	4	**25**
	GP	0.23	0.65	0.150	1	**09**	0.66	0.152	5	**08**	0.63	0.146	3	**14**
	CC	0.18	0.59	0.106	5	**29**	0.61	0.109	4	**28**	0.55	0.100	5	**35**

Step 10 - The SMPI values of material alternatives concerning to the three phases of material lifecycle are evaluated corresponding to SEET indicators using Equations (6.32 – 6.35).

$$SMPI_{Si}^{k} = \sum_{j=1}^{a} C_{ij} \times \sum_{j=1}^{a} RII_{ij}^{k} \qquad \text{(Eq 6.32)}$$

$$SMPI_{Ei}^{k} = \sum_{j=1}^{b} C_{ij} \times \sum_{j=1}^{b} RII_{ij}^{k} \qquad \text{(Eq 6.33)}$$

$$SMPI_{ECi}^{k} = \sum_{j=1}^{c} C_{ij} \times \sum_{j=1}^{c} RII_{ij}^{k} \qquad \text{(Eq 6.34)}$$

$$SMPI_{Ti}^{k} = \sum_{j=1}^{d} C_{ij} \times \sum_{j=1}^{d} RII_{ij}^{k} \qquad \text{(Eq 6.35)}$$

$SMPI_S$, $SMPI_E$, $SMPI_{Ec}$, $SMPI_T$ are Sustainable Material Performance Indices for Social, Environmental, Economic, Technological indicators (SEET) respectively, for each i^{th} alternative and the same is represented in Table 6.27. The letters a, b, c, d represent the total number of factors corresponding to Social, Environmental, Economical and Technological indicators respectively (Refer Table 6.2).

The SMPI values of the material are pooled across the three phases of lifecycle considering SEET indicators using Equation 6.36, and the overall SMPI values are determined using Equation 6.37.

$$SMPI_{i}^{k} = \sum_{k} (SMPI_{Si}^{k} + SMPI_{Ei}^{k} + SMPI_{ECi}^{k} + SMPI_{Ti}^{k}) \qquad \text{(Eq 6.36)}$$

$$Overall.SMPI_{i} = \prod_{k=1}^{z} SMPI_{i}^{k} \qquad \text{(Eq 6.37)}$$

Table 6.27 SMPI values of various material alternatives for the three Lifecycle Phases

Indicators/ Phases	Environmental			Economic			Social			Technological			Phase-wise SMPI			Overall SMPI
Alternatives	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	
OPC	2.26	2.47	2.71	1.99	2.15	2.33	0.93	0.98	0.99	0.44	0.47	0.49	5.62	6.07	6.52	**6.06**
PPC- F	3.75	3.81	4.13	3.05	3.14	3.26	1.16	1.20	1.23	0.49	0.53	0.53	8.45	8.67	9.15	**8.76**
PPC- S	3.82	3.72	4.05	2.98	2.99	3.08	1.05	1.03	1.08	0.47	0.51	0.51	8.32	8.26	8.72	**8.43**
GP	5.83	5.98	5.93	3.08	3.31	3.33	0.88	0.91	0.92	0.56	0.58	0.58	10.35	10.77	10.76	**10.63**
CC	4.12	4.09	4.42	2.69	2.68	2.84	0.97	0.92	0.95	0.42	0.44	0.44	8.20	8.13	8.65	**8.32**

P1, P2, and P3 represent Pre-Construction, Construction and Post-Construction phases respectively. The evaluation procedure to derive the SMPI values is similar to that of the evaluation of alternate binding material (Steps 1 to 10 of Section 6.7.2), which is a standard case for comparison.

6.7.3 Validation (Case Study)

The methodological framework developed is explained in the previous sections and is validated for the results obtained by varying the weights of alternatives, RII values of the three phases and also the weight of SEET indicator. Consequently, it aids in analyzing and comparing the numerical application and describe the performance of material towards sustainability in each case.

- Firstly, with the change in the AHP score of material alternatives in Tables (6.22 – 6.25), the effect on SMPI value is examined. The results are shown in Table 6.28.
- Secondly, with the change in the weight of RII value of life cycle phases, the effect on SMPI value is examined and the results are shown in Table 6.29.

In each of the two cases, uncertainty in expert's perception due to change in time, location, knowledge levels, awareness on sustainable materials and availability of material can certainly affect the sustainable performance of the material. For example, due to varied climate, culture, and geographical location in developing countries like India, material sustainability can affect one or more sustainable factors in the three phases of the material life cycle.

6.7.4 Sensitivity Analysis

Assuming that all the sustainable indicators are equally important, two parameters are taken up for discussion to facilitate the investigation of the relative importance of alternative, indicators and material lifecycle over SMPI (Table 6.28).

The first Parameter (C1) investigates the change in the relative scores of an alternative material with reference to an indicator (SEET) on SMPI, while the second parameter (C2) deals with the change in SMPI value with change in RII value in each phase. The investigation of these parameters is based on the sensitivity analysis.

C-1(a) Environmental indicator: With the change in the relative score of an alternative PPC-F with reference to environmental indicator from 1.19 (Table 6.22) to say a value 2.19 (arbitrary value), the $SMPI_E$ values changes to 6.90, 7.01 and 7.59 which were initially 3.75, 3.81 and 4.13 respectively corresponding to the three phases.

C-1(b) Economic indicator: With the change in the relative score of say Geopolymer material as an alternative with respect to economic indicator from 1.12 (Table 6.23) to 1.47 (arbitrary value), the $SMPI_{Ec}$ value changes from 3.08, 3.31 and 3.33 in three phases to 4.04, 4.34 and 4.37 respectively.

C-1(c) Social indicator: With the change in the relative score of PPC-F from 0.69 (Table 6.24) of social indicator to 0.39 (arbitrary value), the $SMPI_S$ value changes to 0.66, 0.68 and 0.69 from 1.16, 1.20 and 1.23 in the three phases respectively.

C-1(d) Technological indicator: In case of OPC with the change in the relative score from 0.41 (Table 6.25) to 0.24 (arbitrary value) in technological indicator, the $SMPI_T$ value changes to 0.26, 0.27 and 0.29 instead of 0.44, 0.47 and 0.49 corresponding to the three phases (i.e., Pre-construction, During Construction and Post-Construction respectively.

The second parameter studies the change in SMPI values with the changes in RII value in different phases of construction. In this part, the indicators Environmental, Economic and Social which are important to the corresponding phases are mentioned in Table 6.29 and were considered as per the Triple Bottom line approach.

C-2(a) (Pre-construction Phase): From Table 6.29 it can be observed that, with the change in the RII values in the Pre-Construction Phase of all the alternatives with respect to environment indicator to say 4.0 (arbitrary value), the $SMPI_E$ value of the material changes to 3.40, 4.76, 4.68, 6.36 and 4.96 respectively.

C-2(b) (During Construction): With the change in the RII value in the Construction Phase of all alternatives under an economic indicator to say 4.0, the $SMPI_{Ec}$ value of the material changes to 3.24, 4.48, 4.24, 4.88 and 4.04 respectively.

C-2(c) (Post-Construction): With the change in the RII value under the Post-Construction phase of all alternatives in social indicator to say 3.0, the $SMPI_E$ value of the material changes to 1.71, 2.07, 1.83, 1.65 and 1.74 respectively.

The above is an example to demonstrate the sensitivity of the SMPI values with respect to the changes in RII values.

Table 6.28 Changes in SMPI value with the change in AHP score of material alternative

Material lifecycle phases		Pre- Construction Phase					Construction Phase					Post- Construction Phase				
Alternatives		**OPC**	**PPC-F**	**PPC-S**	**GP**	**CC**	**OPC**	**PPC-F**	**PPC-S**	**GP**	**CC**	**OPC**	**PPC-F**	**PPC-S**	**GP**	**CC**
SMPI value for various Alternatives	**ENV**	2.28	3.75	3.82	5.83	4.12	2.50	3.81	3.72	5.98	4.09	2.47	4.13	4.05	5.93	4.42
	ECO	1.99	3.05	2.98	3.08	2.69	2.15	3.14	2.99	3.31	2.68	2.33	3.26	3.08	3.33	2.84
	SOC	0.93	1.16	1.05	0.88	0.97	0.98	1.20	1.03	0.91	0.92	0.99	1.23	1.08	0.92	0.95
	TECH	0.44	0.49	0.47	0.56	0.42	0.47	0.53	0.51	0.58	0.45	0.49	0.53	0.51	0.58	0.44
Case 1	Case 1a	2.28	**6.90**	3.82	5.83	4.12	2.50	**7.01**	3.72	5.98	4.09	2.74	**7.59**	4.05	5.93	4.42
	Case 1b	1.99	3.05	2.98	**4.04**	2.69	2.15	3.14	2.99	**4.34**	2.68	2.33	3.26	3.08	**4.37**	2.84
	Case 1c	0.93	**0.66**	1.05	0.88	0.97	0.98	**0.68**	1.03	0.91	0.92	0.99	**0.69**	1.08	0.92	0.95
	Case 1d	**0.26**	0.49	0.47	0.56	0.42	**0.27**	0.53	0.51	0.58	0.45	**0.29**	0.53	0.51	0.58	0.44

Table 6.29 Changes in SMPI value with the change in RII weights of lifecycle phases

Material lifecycle phases	Pre-Construction		During Construction		Post-Construction	
Indicator / Alternatives	**ENV**	C-2(a)	**ECO**	C-2(b)	**SOC**	C-2(c)
OPC	2.28	3.40	2.15	3.24	0.99	1.71
PPC- F	3.75	4.76	3.14	4.48	1.23	2.07
PPC- S	3.82	4.68	2.99	4.24	1.08	1.83
GP	5.83	6.36	3.31	4.88	0.92	1.65
CC	4.12	4.96	2.68	4.04	0.95	1.74

The Technological aspect as mentioned earlier is added to analyze the SMPI values in the three phases of material lifecycle to uphold the concept of 3R's on various alternatives considering the three phases as per the triple-bottom-line approach (Table 6.30). With the change in RII weight for each of the alternatives in the three phases of lifecycle to 3, 4 and 5 respectively, there is a change in the $SMPI_T$ values in the respective phases (Table 6.30).

Table 6.30 Changes in SMPI value in Technological indicator with change in RII weights of lifecycle phases

Material lifecycle phases	**Pre-Construction**		**During Construction**		**Post-Construction**	
Indicator / **Alternatives**	**TECH**	C-2(d)	**TECH**	C-2(d)	**TECH**	C-2(d)
OPC	0.44	1.23	0.47	1.64	0.49	2.05
PPC- F	0.49	1.32	0.53	1.76	0.53	2.20
PPC- S	0.47	1.26	0.51	1.68	0.53	2.10
GP	0.56	1.41	0.58	1.88	0.59	2.35
CC	0.42	1.14	0.45	1.52	0.44	1.90

It can be observed that the alternative material 'GP' is having highest SMPI (Table 6.27). It shows that the concept of 3R's holds good for Geopolymer based concrete.

From the above discussion, it can be noted that higher the values of relative score of a certain alternative, greater is the SMPI value of that material. Higher the RII weight of a certain lifecycle phase, greater is material sustainability in the respective phase. Conversely, lower the value, lesser is the SMPI value of the material. With this concept, different materials can be compared to evaluate sustainability considering Social, Environmental, Economic and Technological (SEET) indicator. In addition to this, it can be noted that the relative weight of each material and RII of each phase has a different impact on the sustainable factors depending upon their interrelationship.

6.8 Summary of Phase – III study

From Table 6.31, A comparison of the three methods EFTOPSIS, MSPS, and SMPI is made for prioritizing the method and material alternative. It can be observed that in the method I (i.e., EFTOPSIS) the material alternative, 'Fly ash based Portland Pozzolana Cement' (PPC-F) attained the highest closeness coefficient (0.549) and prioritized among Five alternatives. But, in case of method II (MSPS) & method III (SMPI), the material alternative

‘Geopolymer’ got the priority. The material alternative ‘Composite Cement’ has the least prioritization and in all the three methods. The reason and justification for this difference in prioritization of material alternative in the method I and methods (II and III) could be as follows:

1) Method I (EFTOPSIS) do not consider the interdependency between factors, instead, it incorporates the subjective and objective weights of factors using fuzzy and entropy concepts.
2) The methods I and II do not consider the significance of three life cycle phases, but method III incorporates the material life cycle with respect to factors and observes the material performance in each case.
3) The methods II and III utilizes the concept of pairwise comparison (AHP) in determining the relative weights for factors and alternatives. Also, these methods prioritize the material alternatives considering SEET indicators, a preference based prioritization towards sustainability, which is not the case with method I.
4) The methods (I and II) utilize the concepts of MCDM in prioritizing the material alternative, while method III utilizes both the concepts of Life cycle assessment and MCDM. Hence, it can be used to prioritize, without the need for Life cycle inventory data.

The present research study observed the individual competence of the three proposed methods and based on the results suggests method III (SMPI) in view of its robustness and flexibility in prioritizing the material alternative without the need for inventory data. Even with inventory data for building materials, method III can accommodate this data in the selection of sustainable material. This shows the flexibility and simplicity of prioritizing the material alternative.

Table 6.31 Prioritization of material alternative for the three methods

Material Alternative	**Prioritization of material alternative**		
	EFTOPSIS (Method I)	**MSPS (Method II)**	**SMPI (Method III)**
OPC	3	5	5
PPC - F	1	2	2
PPC - S	2	3	3
GP	4	1	1
CC	5	4	4

This phase of work has ascertained 10 significant sustainable factors, keeping in view, the Quadra-Bottom Line indicators i.e., Social, Environmental, Economic and Technological (SEET) involving various stakeholder’s perceptions for implementing sustainable practices by choosing an appropriate sustainable material alternative. The theories of Multi-Criteria Decision Making (MCDM) in prioritizing the material alternative was employed and their prominence and competence in considering various strategies, inputs, and outputs was noted. Three methods – Entropy-based FTOPSIS (EFTOPSIS), Material Sustainable Performance (MSPS), and Sustainable Material Performance Index (SMPI) were employed and it was noticed that SMPI method is more relevant in selecting the most sustainable material alternative. The following are the specific conclusions from the chapter.

1. The significance of adopting material life cycle in the selection of sustainable material was revealed by considering three methods of evaluation (viz. EFTOPSIS, MSPS, and SMPI).
2. The results of the study highlights the flexibility and simplicity of Sustainable Material Performance Index (SMPI) method in determining the quantitative performance index value.
3. The method (SMPI) evaluates the material sustainability performance considering the three phases of Lifecycle based on qualitative and quantitative approach without the need for Life Cycle Inventory (LCI) data.
4. The SMPI for a certain building material is developed using the Analytical Hierarchy Process (AHP), an MCDM approach. Relative Importance Index (RII) a statistical technique was used for evaluating the composite priorities in material selection in the three phases of the lifecycle.
5. One major outcome of the study is the encouraging values of RII for Supplementary Cementitious Material (SCM) alternatives like PPC-F, PPC-S, and CC. Also, the indicator ‘Construction and Demolition waste’ has higher values of RII in the Pre-Construction and Post-Construction phases which eventually reveals the concept of 5R’s (Reduce, Re-use, Replace, Repair and Renovate). This is one important step towards sustainability.
6. From the global SMPI values along with the various sustainable factors and indicators (SEET) considering the three Lifecycle phases, the material alternative

‘Geopolymer’ has emerged as the material with higher SMPI value, while ‘OPC’ has the least SMPI.

7. The overall sustainable prioritization of material alternatives is in the order of GP, PPC-F, PPC-S, CC and OPC with SMPI values 10.63, 8.75, 8.43, 8.32 and 6.08 respectively.
8. Considering various sustainable factors with equal importance in all the three phases, the ranking of the RII is in the order of Post-construction (36.72%), Pre-construction (30.21%) and during construction phases (34.07%).
9. From the study, it was found rational to include Technological Indicator also has a significant place for the various factors considered.

The developed conceptual framework is a simple, robust and flexible framework which can provide valuable inputs for building professionals and assist them in making critical decisions while choosing the sustainable alternative material.

Based on the relative weights of criteria, indicators and attribute credit points, a user interface seems to simply the evaluation system. Chapter 7 emphasizes on developing a Graphical User Interface (GUI) for Sustainable Building Assessment Tool (SBAT) for the ease of use, which acts as a self-assessment tool for the users of the building.

Chapter - 7

DEVELOPMENT OF AN AUTOMATED SUSTAINABLE BUILDING SCORING SYSTEM

Phase IV

To establish a sustainable building performance scoring system based on relative weights of criteria and credit points of sustainable attributes and develop an automated graphical user-interface tool (SBAT).

7.0 General

A scoring system is an integral part of any assessment tool. The relative weights obtained for sustainable SEET indicators, sustainable criteria and attributes enable to allocate and measure the performance of the building (Chapters 4 & 5). To assess the building performance, relative weights are assigned to criteria and global weights to attributes as explained in the previous chapters. The present chapter emphasizes on how a preference-based sustainable building score and an overall Sustainable Building Performance Score (SBPS) considering SEET indicators are developed. Based on the credit points (global weights) allocated to 37 attributes, the performance of sustainable criteria are assessed. Similarly, based on the relative weights assigned to sustainable SEET indicators, the preference-based sustainable performance of the building is assessed. Further, based on the SBPS obtained, a star rating is assigned to categorize sustainable performance of the building, similar to other building assessment tools. A Graphical User Interface (GUI), which acts as a self-assessment tool for the users of the building to identify the potential gaps and improvements in attaining a status of sustainable building is identified. A Quick Response (QR) code was embedded to the web portal for the assessment tool to improve awareness and public outreach.

7.1 Sustainable Building Performance Score (SBPS)

The sustainable performance of a building represented can be a single score (Shareef & Altan, 2017). In the present work, a simple additive process is employed to evaluate the building performance and thus attain a Sustainable Building Performance Score (SBPS).

To calculate SBPS, the relative weights of eight sustainable criteria and global credit points of 37 sustainable attributes obtained as explained in Chapter 5 are utilized.

The assigned credit points to attributes are added up to obtain the respective weighted scores for each of the sustainable criteria. Similarly, the points obtained for every criterion are summed up to get overall SBPS for a certain building. The SBPS for each sustainable criteria for a particular building is obtained from Equations (7.1 to 7.8). The letter 'A' denotes the attribute and the letter 'm' represents the total number of attributes corresponding to each criterion (Table 5.1 of Chapter 5)

The Sustainable Building Performance with respect to a certain criteria say, Water Efficiency (WE) is obtained by using Equation 7.1

$$WE = \sum_{i=1}^{m} A_i \qquad \text{(Eq 7.1)}$$

Similarly, the Sustainable Building Performance with respect to other criteria can also be obtained by taking the weighted sum of the attributes.

After evaluating the Sustainable Building Performance of all the criteria like Water Efficiency (WE), Material and Waste Management (MW), Health and Well-being (HW), Energy Efficiency (EE), Sustainable Sites (SS), Social Welfare (SW), Transportation (T), and Management (M), the overall SBPS is calculated based on simple additive Equation 7.2.

$$SBPS = \sum(WE + MW + HW + EE + SS + SW + T + M) \qquad \text{(Eq. 7.2)}$$

The preference-based sustainable performance of a certain building can be assessed by considering the Social (S), Environmental (En), Economic (E), and Technological (T) (SEET) indicators evaluated using Equations (7.3 to 7.6).

$$SBPS_S = 0.21\sum(WE + MW + HW + EE + SS + SW + T + M) \qquad \text{(Eq. 7.3)}$$

$$SBPS_{En} = 0.30\sum(WE + MW + HW + EE + SS + SW + T + M) \qquad \text{(Eq. 7.4)}$$

$$SBPS_E = 0.22\sum(WE + MW + HW + EE + SS + SW + T + M) \qquad \text{(Eq. 7.5)}$$

$$SBPS_T = 0.27\sum(WE + MW + HW + EE + SS + SW + T + M) \qquad \text{(Eq. 7.6)}$$

To differentiate the building performance towards sustainability, based on the Sustainable Building Performance Score (SBPS), the building is categorized under five different performance levels. The proposed performance levels are shown in Table 7.1

Table 7.1 Performance level based on Sustainable Building Performance Score (SBPS)

Performance Level		**Sustainable Building Performance Score (SBPS)**
One Star	★	30 - 44
Two Star	★★	45 – 59
Three Star	★★★	60 – 74
Four Star	★★★★	75 – 89
Five Star	★★★★★	>=90

7.2 Sustainable Building Assessment Tool (SBAT)

A web-based design consisting of a framework considering the various criteria and attributes has been developed. A user interface system between the client and framework can make things comprehensive and enhance the execution.

In the present study, to create a Graphic User Interface (GUI) for the framework developed, (SBAT) the study used open-source software and technologies (Tomcat Apache server, JavaScript, Java Server Pages, and HTML). The development of GUI is represented in Fig. 7.1. The Hypertext Markup Language (HTML), is utilized to view the designed document on the web browser. The appearance of the document is assisted by Cascading Style Sheets (CSS) and scripting languages such as JavaScript (JS), a programming language that adds a dynamic feature to the GUI system. HTML acts as a front end to interact with users and refers to the client-side of the application. The Java Server Pages (JSP) generates a dynamic webpage on HTML and using a compact web server like Apache Tomcat one can run the Java code and handle request and response from client-side.

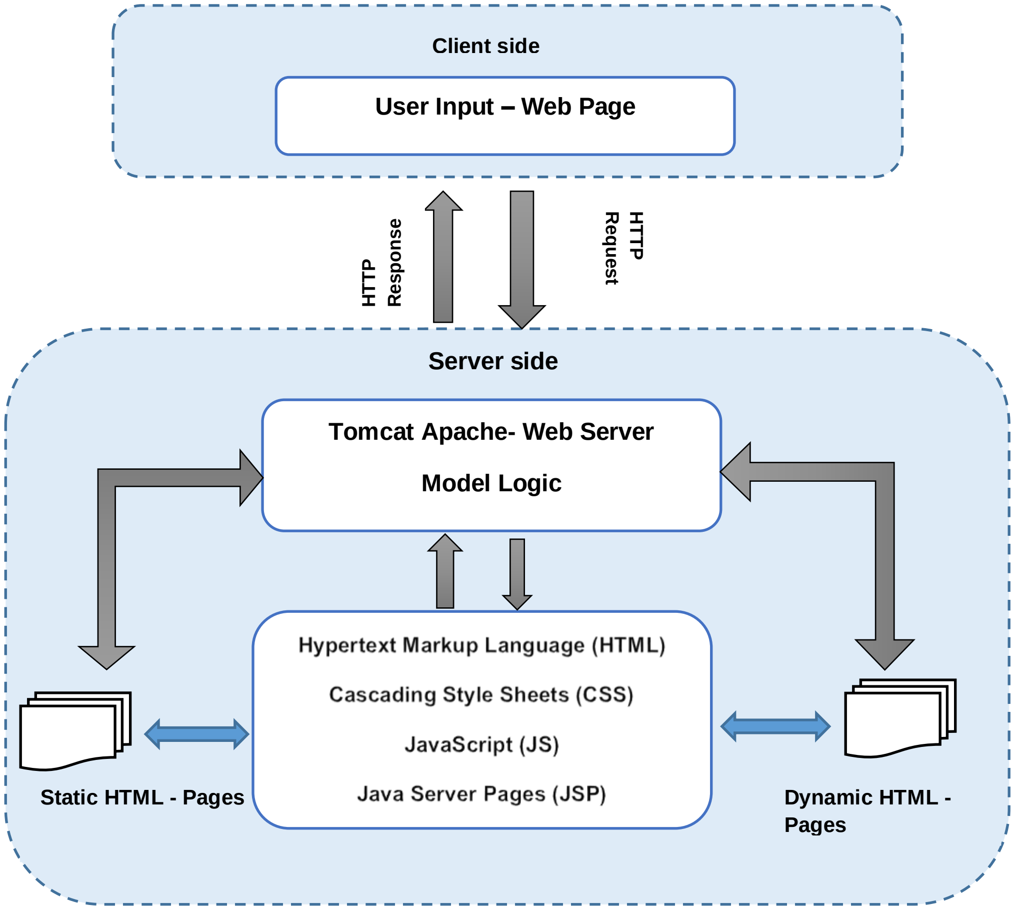


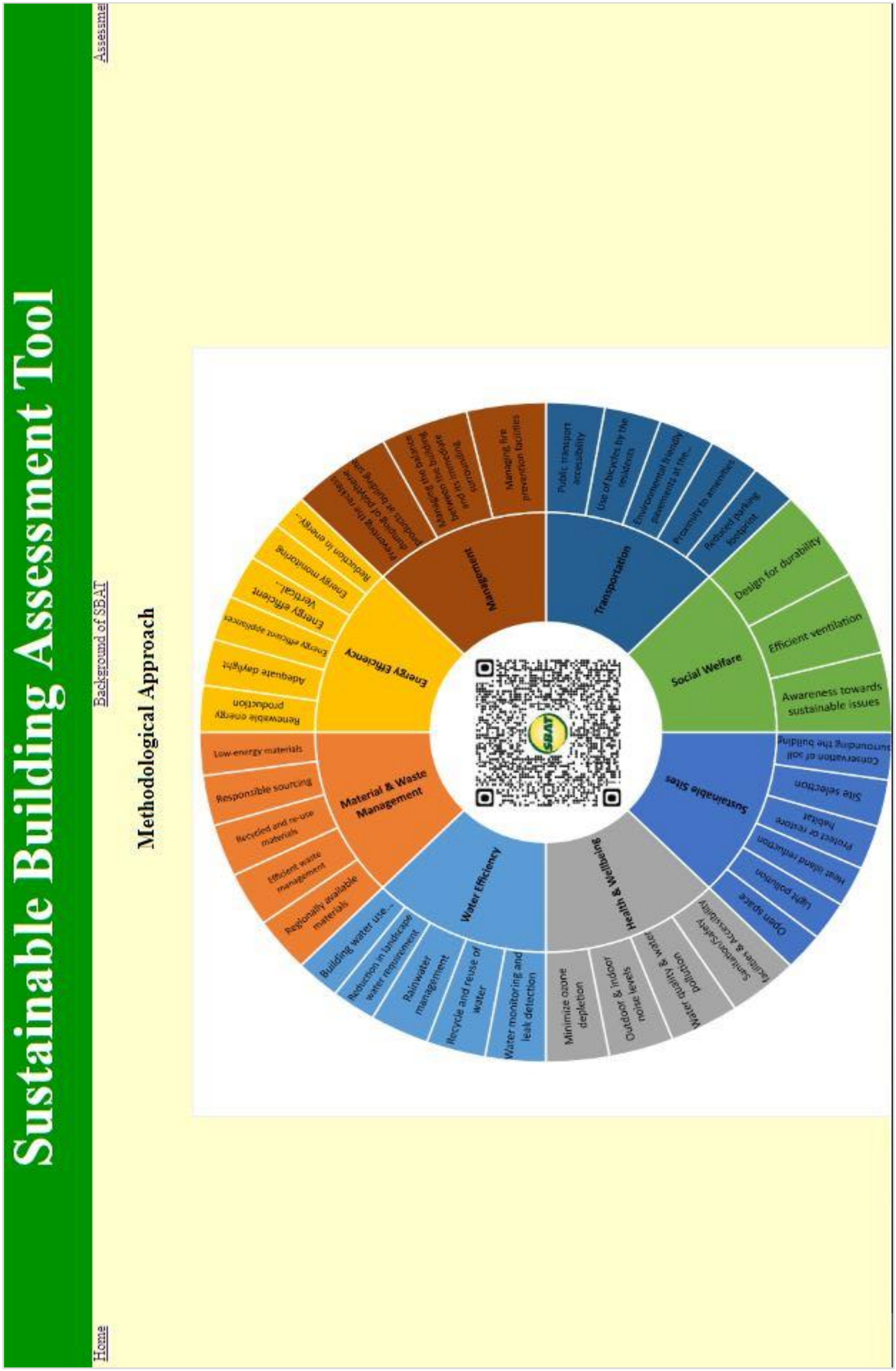
Fig 7.1 Schematic diagram for the development of GUI

7.3 Discussion

The GUI thus developed is explained in the subsequent pages. In the first page, the users are advised/suggested projected to read the general information about the tool (SBAT) before using it, under 'HOME' page. The general information involves the aim, objective, benefits, considerations for the development of the tool and the expected outcome of the SBAT tool (Table. 7.2). The second page under the navigation button 'BACKGROUND' shown in Fig. 7.2, represents the details of the methodological approach involved in development of SBAT framework. The significant criteria, indicators, attributes, and their relative weights and interrelation weights are represented for better understanding, before using the assessment web page (third page).

Fig 7.2 Background information on SBAT on the web page

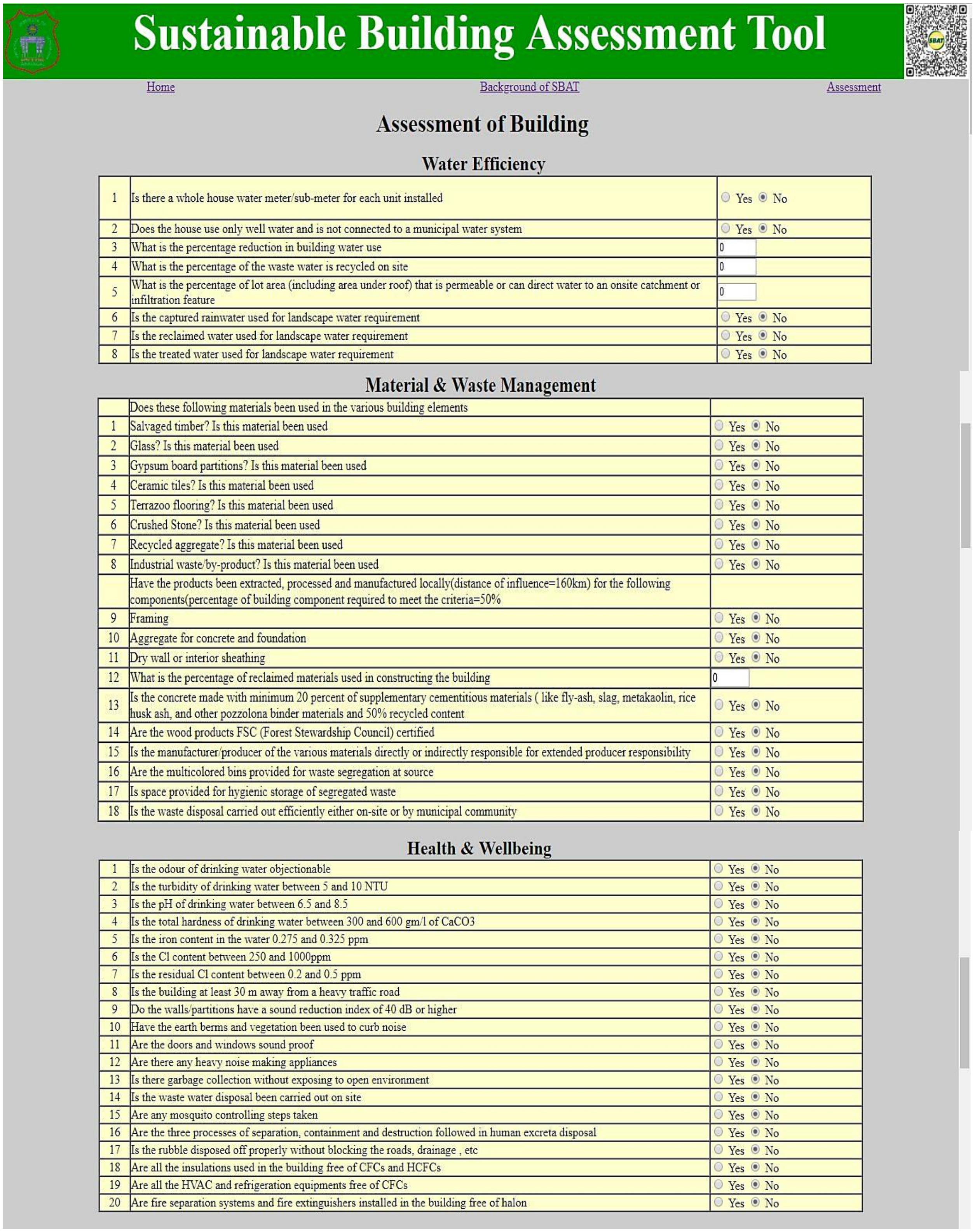
Table 7.2 General information of SBAT on the web page



The third page under the navigation button ‘ASSESSMENT’ shown in Table. 7.3 ((a) & (b)) shows the questionnaire for assessing certain building performance. The questionnaire is based on two types: Yes/No and Percentage based. Based on the response, the credit points are evaluated for the respective criteria (8 No’s) and the SBAT analysis is shown as an output (Fig. 7.3) for some random inputs after submitting the assessment using ‘SUBMIT’ button at the bottom of the page.

The analysis is carried out with random inputs for the questionnaire with regard to Eight criteria, and the output result is represented by a Sustainable Building Score (SBS) (achieved score). Also, the preference-based SBS with respect to SEET indicators are shown in Fig. 7.3.

Table 7.3 (a) & (b) Input assessment page of GUI



Sustainable Building Assessment Tool

Home | Background of SBAT | Assessment

Assessment of Building

Water Efficiency

1	Is there a whole house water meter/sub-meter for each unit installed	Yes No
2	Does the house use only well water and is not connected to a municipal water system	Yes No
3	What is the percentage reduction in building water use	0
4	What is the percentage of the waste water is recycled on site	0
5	What is the percentage of lot area (including area under roof) that is permeable or can direct water to an onsite catchment or infiltration feature	0
6	Is the captured rainwater used for landscape water requirement	Yes No
7	Is the reclaimed water used for landscape water requirement	Yes No
8	Is the treated water used for landscape water requirement	Yes No

Material & Waste Management

	Does these following materials been used in the various building elements	
1	Salvaged timber? Is this material been used	Yes No
2	Glass? Is this material been used	Yes No
3	Gypsum board partitions? Is this material been used	Yes No
4	Ceramic tiles? Is this material been used	Yes No
5	Terrazoo flooring? Is this material been used	Yes No
6	Crushed Stone? Is this material been used	Yes No
7	Recycled aggregate? Is this material been used	Yes No
8	Industrial waste/by-product? Is this material been used	Yes No
	Have the products been extracted, processed and manufactured locally(distance of influence=160km) for the following components(percentage of building component required to meet the criteria=50%	
9	Framing	Yes No
10	Aggregate for concrete and foundation	Yes No
11	Dry wall or interior sheathing	Yes No
12	What is the percentage of reclaimed materials used in constructing the building	0
13	Is the concrete made with minimum 20 percent of supplementary cementitious materials (like fly-ash, slag, metakaolin, rice husk ash, and other pozzolona binder materials and 50% recycled content	Yes No
14	Are the wood products FSC (Forest Stewardship Council) certified	Yes No
15	Is the manufacturer/producer of the various materials directly or indirectly responsible for extended producer responsibility	Yes No
16	Are the multicolored bins provided for waste segregation at source	Yes No
17	Is space provided for hygienic storage of segregated waste	Yes No
18	Is the waste disposal carried out efficiently either on-site or by municipal community	Yes No

Health & Wellbeing

1	Is the odour of drinking water objectionable	Yes No
2	Is the turbidity of drinking water between 5 and 10 NTU	Yes No
3	Is the pH of drinking water between 6.5 and 8.5	Yes No
4	Is the total hardness of drinking water between 300 and 600 gm/l of CaCO3	Yes No
5	Is the iron content in the water 0.275 and 0.325 ppm	Yes No
6	Is the Cl content between 250 and 1000ppm	Yes No
7	Is the residual Cl content between 0.2 and 0.5 ppm	Yes No
8	Is the building at least 30 m away from a heavy traffic road	Yes No
9	Do the walls/partitions have a sound reduction index of 40 dB or higher	Yes No
10	Have the earth berms and vegetation been used to curb noise	Yes No
11	Are the doors and windows sound proof	Yes No
12	Are there any heavy noise making appliances	Yes No
13	Is there garbage collection without exposing to open environment	Yes No
14	Is the waste water disposal been carried out on site	Yes No
15	Are any mosquito controlling steps taken	Yes No
16	Are the three processes of separation, containment and destruction followed in human excreta disposal	Yes No
17	Is the rubble disposed off properly without blocking the roads, drainage , etc	Yes No
18	Are all the insulations used in the building free of CFCs and HCFCs	Yes No
19	Are all the HVAC and refrigeration equipments free of CFCs	Yes No
20	Are fire separation systems and fire extinguishers installed in the building free of halon	Yes No

(a)

Energy Efficiency

1	What is the total renewable energy produced per year by the system?(in kWh)	0
2	Are the refrigerators BEE qualified	○ Yes ◉ No
3	Are the ceiling fans BEE qualified	○ Yes ◉ No
4	Are the other devices (washing machines, dish washers, etc) BEE qualified	○ Yes ◉ No
5	Is there a meter/sub-meter fo each residential unit instaled	○ Yes ◉ No
6	What is the percentage reduction in energy consumption associated with the interior lighting over baseline power density of 0.48W/Sqft or 5.2 W/sqm	0
7	What is the daylight factor of the building (in percentage)	0
8	Are the vertical transportation systems(elevators, escalators ,etc) are BEE certified	○ Yes ◉ No

Sustainable Sites

1	Does the site consist of prime farmland	○ Yes ◉ No
2	Does the site lie within a flood hazard area	○ Yes ◉ No
3	Is the site near to an area which is home for species listed as threatned or endangered	○ Yes ◉ No
4	Is the site near to an area which is home for species listed as threatned or endangered	○ Yes ◉ No
5	What is the percentage area with shading/non-absorptive material	0
6	Is there a publicly accessible or community based open space that is at least 3/4 acre within 800m radius	○ Yes ◉ No
7	Are there 2 smaller open spaces totalling 3/4 acre	○ Yes ◉ No
8	Is there a publicly available space at the project site	○ Yes ◉ No
9	Do the street lighting luminaries emit any light above 90 degrees (horizintal)	○ Yes ◉ No
10	Is the illumination at property lines zero Footcandles	○ Yes ◉ No
11	Is there uplighting of trees	○ Yes ◉ No
12	Is the top soil suitable for vegetation growth	○ Yes ◉ No
13	Are the fertilizers and manure applied timely to the soil for healthy growth of vegetation	○ Yes ◉ No
14	Is there a good drainage system to avoid water logging	○ Yes ◉ No

Social Welfare

1	Are the product manufacturer's manuals available for all installed equipment, fixtures, appliances, etc.	○ Yes ◉ No
2	Are the residents well aware of efficient use of energy, water and natural resources	○ Yes ◉ No
3	Is the enhanced local exhaust/enhanced whole-house ventilation system installed	○ Yes ◉ No
4	Are there any unvented combustion appliances installed in the building	○ Yes ◉ No
5	Are the floorings water resistant	○ Yes ◉ No
6	Do the floors have enough slopes to drain off the water	○ Yes ◉ No
7	Do the slabs, beams and columns have sufficient cover (as per IS code) to protect the reinforcement from deterioration	○ Yes ◉ No

Transportation

1	Is the bus stop within 640 m radius	○ Yes ◉ No
2	What is the accessibility of the bus stop (in Kilometers)	0
3	Do the residents use bicycles	○ Full ○ Partial ◉ No use
4	How many amenities are within 800m radius from the building site	0
5	Are the pavements at building site environmental friendly	○ Yes ◉ No
6	Is there an underground/ground-level parking garage	○ Yes ◉ No

Management

1	Is the waste disposed openly in the vicinity of the building	○ Yes ◉ No
2	Are the harmful effluents disposed off to the nearby water bodies	○ Yes ◉ No
3	Are the fuel sources away from the areas vulnerable to fire catching	○ Yes ◉ No
4	Are the fire warning systems (sound alarms, engage sprinklers, etc) installed	○ Yes ◉ No
5	Are there fire emergency exits	○ Yes ◉ No
6	Are fire extinguishers and fire hydrants installed	○ Yes ◉ No
7	Are the polythene products being dumped properly at the building site	○ Yes ◉ No

Submit Reset

(b)

Fig 7.3 Output analysis of GUI

Note: WE - Water Efficiency**; MW** - Material & Waste Management**; HW** - Health & Wellbeing**;**
EE - Energy Efficiency**; SS** - Sustainable Sites**; SW** - Social Welfare**; T** - Transportation**; M** - Management

Keeping in view, the growing public support towards digitalization, digital wallets and QR codes in India, the present work enabled to increase the public outreach and responsiveness for the newly developed SBAT by creating QR code link as shown in Fig 7.4, embedded to an online web link created in google drive for saving the user response data. The web link provided below directs to google drive questionnaire survey page (Fig 7.5).

(https://onedrive.live.com/survey?resid=117FF9B2D825E0CB!105&authkey=!APTgJn1witBTslY).

In this way, the SBAT is further simplified as a self-assessment tool to store data given by a building user, to serve as a database to assess the Sustainable Building Performance Score.

Fig. 7.4 QR code for SBAT framework

By scanning the above mentioned QR code (Fig. 7.4), the browser page appears as shown in Fig.7.5, where the user needs to respond to the questionnaire and submit the form for further evaluation. The user can even respond using mobile android phones from any location as well.

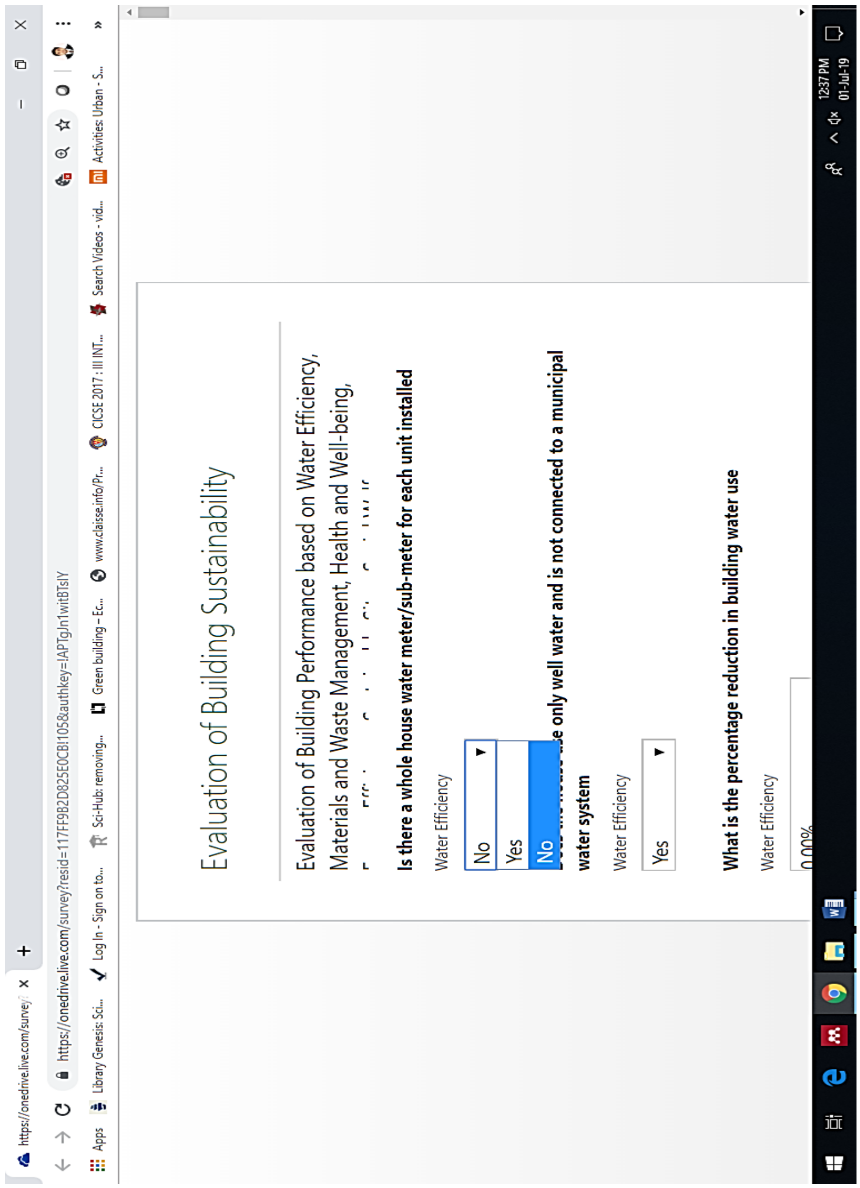


Fig. 7.5 Online Excel google drive web portal assessment page

7.3.1 **Validation of the SBAT framework**

The framework SBAT thus developed is validated by observing the performance of a building which is formerly rated by a prominent assessment tool like LEED. For this, an existing building which has been awarded as first LEED platinum-rated building in India was chosen and using the presently developed SBAT tool, the same is rated.

7.3.2 Case Study

The Confederation of Indian Industry (CII) a non-government and non-profitable organization constructed a Business Centre - Sohrabji Godrej at Hyderabad, India which is a unique Public and Private Partnership project. The details of the project are shown in Fig 7.6. This Business Centre is rated as the first platinum-rated building in India by the LEED – New Construction (NC) V 2.0 assessment rating tool and achieved 56 credit points in the year 2003. Some of the remarkable achievements of the building are as follows: 1) About 55 – 60% is covered with vegetated roof covers and remaining space is covered with solar panels of 24W capacity. 2) Nearly, 100 to 200 units of power are fed into the nearest grid. 3) The building reduces 38% of municipal water utilization by using low-flush toilets and waterless urinals. 4) The building is constructed utilizing the regionally available materials. The use of natural ventilation and lighting has improved the energy-efficiency strategies of the building. 5) The green spaces provided in and around the building help in controlling the micro-climate, the visual effects and the daylight performance.

The aerial view of CII-Godrej, Hyderabad with Solar panels and wind tower is shown in Fig 7.6. The following sections describe some of the CII – Godrej building sustainability aspects considered while assessing the performance of the building.

Fig. 7.6 Aerial view of CII-Godrej, Hyderabad with project details

7.3.2.1 Site Location and orientation – Sustainable Sites

The building is located in the prime location in HITEC City, a well-known technology township in Hyderabad (Fig. 7.7). The building encourage the use of alternative energy sourced vehicles to reduce vehicular pollution and save energy.

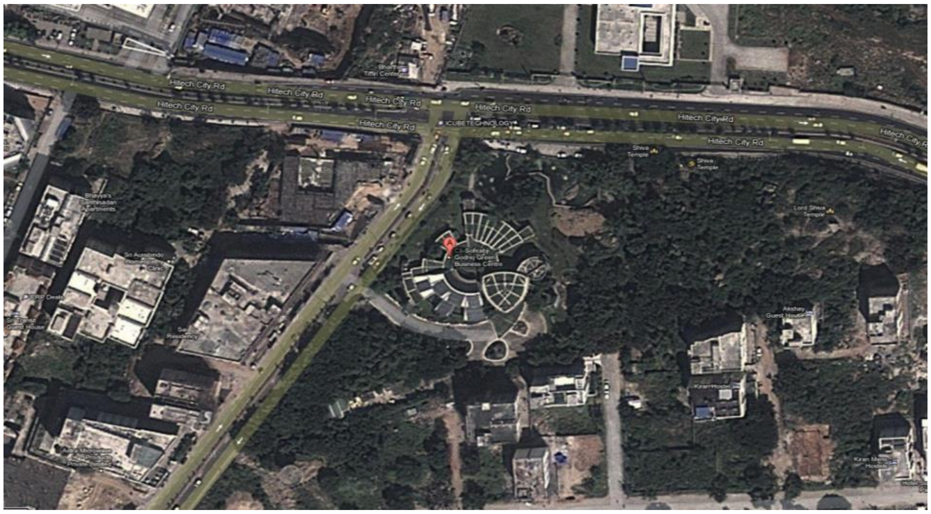


Fig 7.7 Site location and orientation

7.3.2.2 Sustainable ecology system

Without causing disturbance to the local eco-system, the building landform is designed to integrate the existing and prevailing features (Fig. 7.8). The rocks existing on the site have been retained and integrated into the building design

Fig. 7.8 Example of a Sustainable Ecology System

7.3.2.3 Sustainable Design

To reduce the unwanted heat inside the building, the building is designed to maximize the natural ventilation and optimized day-lighting without getting heat inside. For this, roof gardens are provided to act as insulation for heat absorption (Fig 7.9 (a)). Also, Earth Berming and Intelligent window designs are provided to further reduce the heat gain (Fig. 7.9 (b)).

(a)

(b)

Fig 7.9 ((a) – (b)) Heat reduction strategies of the building

a) Roof gardens insulate the building from solar heat.

b) The intelligent design of windows allows light but keep the heat away

The building was designed as an effective combination of closed and open spaces to maintain temperature and micro-climate (Fig. 7.10).

Fig. 7.10 Integration of open and closed spaces to maintain the temperature

7.3.2.4 Use of low-embodied materials

To reduce the embodied energy, the building utilized local materials at all possible places. For instance, local stone and waste construction materials are used for external cladding and old furniture has been used in different parts of the building (Fig. 7.11).

(a) (b)

Fig. 7.11 ((a) - (b)) Use of low-embodied materials
a) Stone and wood - locally available materials utilized
b) Use of refurbished materials for making new furniture.

7.3.2.5 Daylighting and Ventilation

To provide proper day-lighting and reduce the heat gain, windows and openings are placed in appropriate locations (Fig. 7.12).

(a) (b)

Fig. 7.12 ((a) - (b)) Orientation of building and window placing
a) Windows at appropriate locations
b) Open space for heat reduction

Measures are taken to ventilate the building to save energy consumption. A wind tower is provided to catch the air to pre-cool. The outer face of the building is placed with ‘Jaalis’ to facilitate the flow of cool air. This also encourages shading and reduces the direct entry of sunlight into the building (Fig 7.13).

(a)

(b)

Fig 7.13 ((a) – (b)) Installation of Wind tower and Jaalis

7.3.2.6 Renewable Energy

The building was installed with a roof-top photovoltaic solar panel serving as a renewable energy resource (Fig. 7.14).

Similarly, the use of alternatively resourced energy vehicles is encouraged. The total energy savings of the building is about 55% (Asian Business Council report 2004).

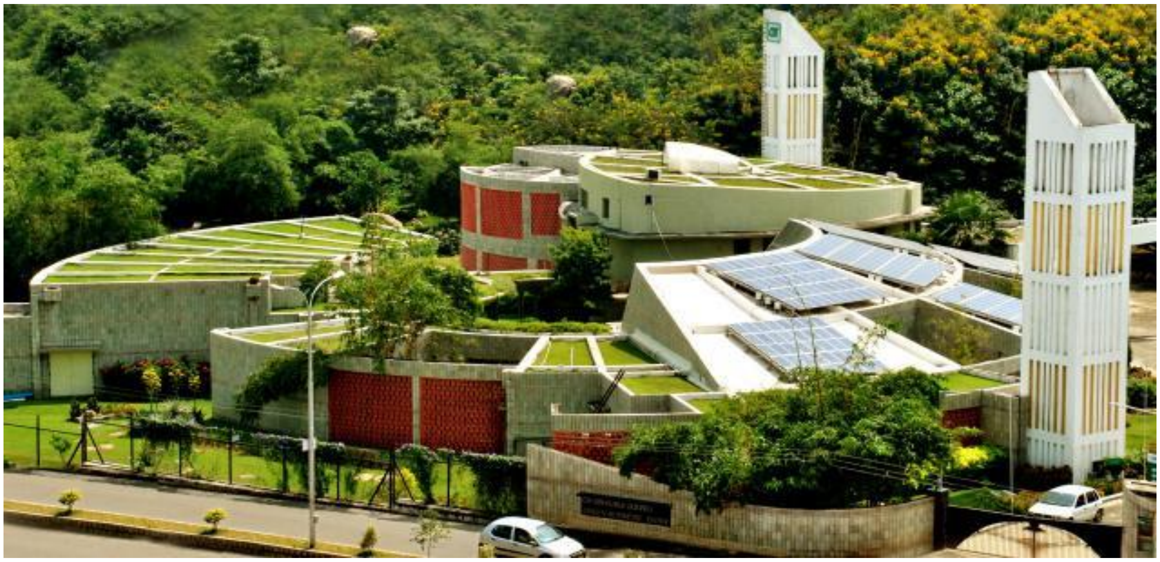


Fig 7.14 Installation of Solar Roof-top panels
(Source:http://www.asiabusinesscouncil.org/ResearchBEE-4.html)

7.3.2.7 Water Efficiency and Management

Efficient water fixtures are utilized to reduce the consumption of water. Further, rainwater is managed to recharge the ground. To reduce the consumption of water, local plants and trees are encouraged in the landscaping design of the garden. The treated water is routed properly to be utilized for flushing toilets and irrigating the garden. The wastewater treatment plant is installed at an appropriate location to treat the water (Fig 7.15).

(a) (b)

Fig. 7.15 Water Management

The LEED certification for the CII Godrej building by LEED V 2.0 is shown in Table 7.4 and was awarded a score of 56 points.

CII - Sohrabji Godrej Green Business Centre
Hyderabad, India
LEED® Project # 00169
LEED Version 2 Certification Level: Platinum
October 31, 2003

56 Points Achieved — Possible Points: 69

Certified 26 to 32 points; Silver 33 to 38 points; Gold 39 to 51 points; Platinum 52 or more points

Y		Sustainable Sites (11) — Possible Points: 14	
Y	Prereq 1	**Erosion & Sedimentation Control**	
1	Credit 1	**Site Selection**	1
	Credit 2	**Urban Redevelopment**	1
	Credit 3	**Brownfield Redevelopment**	1
1	Credit 4.1	**Alternative Transportation**, Public Transportation Access	1
1	Credit 4.2	**Alternative Transportation**, Bicycle Storage & Changing Rooms	1
1	Credit 4.3	**Alternative Transportation**, Alternative Fuel Refueling Stations	1
1	Credit 4.4	**Alternative Transportation**, Parking Capacity	1
1	Credit 5.1	**Reduced Site Disturbance**, Protect or Restore Open Space	1
1	Credit 5.2	**Reduced Site Disturbance**, Development Footprint	1
1	Credit 6.1	**Stormwater Management**, Rate and Quantity	1
1	Credit 6.2	**Stormwater Management**, Treatment	1
1	Credit 7.1	**Landscape & Exterior Design to Reduce Heat Islands**, Non-Roof	1
1	Credit 7.2	**Landscape & Exterior Design to Reduce Heat Islands**, Roof	1
	Credit 8	**Light Pollution Reduction**	1

Y		Water Efficiency (5) — Possible Points: 5	
1	Credit 1.1	**Water Efficient Landscaping**, Reduce by 50%	1
1	Credit 1.2	**Water Efficient Landscaping**, No Potable Use or No Irrigation	1
1	Credit 2	**Innovative Wastewater Technologies**	1
1	Credit 3.1	**Water Use Reduction**, 20% Reduction	1
1	Credit 3.2	**Water Use Reduction**, 30% Reduction	1

Y		Energy & Atmosphere (14) — Possible Points: 17	
Y	Prereq 1	**Fundamental Building Systems Commissioning**	
Y	Prereq 2	**Minimum Energy Performance**	
Y	Prereq 3	**CFC Reduction in HVAC&R Equipment**	
2	Credit 1.1	**Optimize Energy Performance**, 20% New / 10% Existing	2
2	Credit 1.2	**Optimize Energy Performance**, 30% New / 20% Existing	2
2	Credit 1.3	**Optimize Energy Performance**, 40% New / 30% Existing	2
2	Credit 1.4	**Optimize Energy Performance**, 50% New / 40% Existing	2
1	Credit 1.5	**Optimize Energy Performance**, 60% New / 50% Existing	2
1	Credit 2.1	**Renewable Energy**, 5%	1
1	Credit 2.2	**Renewable Energy**, 10%	1
	Credit 2.3	**Renewable Energy**, 20%	1
1	Credit 3	**Additional Commissioning**	1
1	Credit 4	**Ozone Depletion**	1
1	Credit 5	**Measurement & Verification**	1
	Credit 6	**Green Power**	1

Y		Materials & Resources (9) — Possible Points: 13	
Y	Prereq 1	**Storage & Collection of Recyclables**	
	Credit 1.1	**Building Reuse**, Maintain 75% of Existing Shell	1
	Credit 1.2	**Building Reuse**, Maintain 100% of Existing Shell	1
	Credit 1.3	**Building Reuse**, Maintain 100% Shell & 50% Non-Shell	1
1	Credit 2.1	**Construction Waste Management**, Divert 50%	1
1	Credit 2.2	**Construction Waste Management**, Divert 75%	1
1	Credit 3.1	**Resource Reuse**, Specify 5%	1
	Credit 3.2	**Resource Reuse**, Specify 10%	1
1	Credit 4.1	**Recycled Content**	1
1	Credit 4.2	**Recycled Content**	1
1	Credit 5.1	**Local/Regional Materials**, 20% Manufactured Locally	1
1	Credit 5.2	**Local/Regional Materials**, of 20% Above, 50% Harvested Locally	1
1	Credit 6	**Rapidly Renewable Materials**	1
1	Credit 7	**Certified Wood**	1

Y		Indoor Environmental Quality (13) — Possible Points: 15	
Y	Prereq 1	**Minimum IAQ Performance**	
Y	Prereq 2	**Environmental Tobacco Smoke (ETS) Control**	
1	Credit 1	**Carbon Dioxide (CO_2) Monitoring**	1
	Credit 2	**Increase Ventilation Effectiveness**	1
1	Credit 3.1	**Construction IAQ Management Plan**, During Construction	1
1	Credit 3.2	**Construction IAQ Management Plan**, Before Occupancy	1
1	Credit 4.1	**Low-Emitting Materials**, Adhesives & Sealants	1
1	Credit 4.2	**Low-Emitting Materials**, Paints	1
1	Credit 4.3	**Low-Emitting Materials**, Carpet	1
1	Credit 4.4	**Low-Emitting Materials**, Composite Wood	1
1	Credit 5	**Indoor Chemical & Pollutant Source Control**	1
1	Credit 6.1	**Controllability of Systems**, Perimeter	1
	Credit 6.2	**Controllability of Systems**, Non-Perimeter	1
1	Credit 7.1	**Thermal Comfort**, Comply with ASHRAE 55-1992	1
1	Credit 7.2	**Thermal Comfort**, Permanent Monitoring System	1
1	Credit 8.1	**Daylight & Views**, Daylight 75% of Spaces	1
1	Credit 8.2	**Daylight & Views**, Views for 90% of Spaces	1

Y		Innovation & Design Process (4) — Possible Points: 5	
1	Credit 1.1	**Innovation in Design**: Exemplary Water Efficiency	1
1	Credit 1.2	**Innovation in Design**: Eco-friendly Housekeeping	1
1	Credit 1.3	**Innovation in Design**: Education on Sustainability	1
	Credit 1.4	**Innovation in Design**:	1
1	Credit 2	**LEED® Accredited Professional**	1

Table 7.4 LEED V 2.0 Certification for CII – Godrej building

(Source:https://s3.amazonaws.com/legacy.usgbc.org/usgbc/docs/Archive/CertifiedProjects/Docs424.pdf)

To perceive the consistency and reliability of the SBAT framework, the study has undertaken an assessment of the same building. This investigation is carried out to observe the practicality and feasibility of the framework. Based on the SBAT framework, the building has attained a score of 76 credit points and is categorized under four-star (Table 7.5). It can be observed that the score attained for SBAT is more than the score awarded by LEED. This could be because, the criteria considered in the SBAT framework, are more tailored to suit the Indian regional conditions and the prevailing factors while LEED is not exactly custom-made for rating buildings in the Indian context. Further, it can be observed that the building has secured all the possible credits allotted for 'Health and Wellbeing', 'Transportation' and 'Management' criteria. Though, the assessment methods LEED and SBAT cannot be compared from the sustainability point of view of a particular building based on their adopted criteria and assessment strategies, the rating of a certain building can be assessed based on the various strategies adopted for the purpose of assessment.

Table 7.5 SBAT Assessment of CII – Godrej building

Home | Background of SBAT | Assessment

Assessment of Building

Water Efficiency

1	Is there a whole house water meter/sub-meter for each unit installed	○ Yes ◉ No
2	Does the house use only well water and is not connected to a municipal water system	○ Yes ◉ No
3	What is the percentage reduction in building water use	35
4	What is the percentage of the waste water is recycled on site	65
5	What is the percentage of lot area (including area under roof) that is permeable or can direct water to an onsite catchment or infiltration feature	60
6	Is the captured rainwater used for landscape water requirement	◉ Yes ○ No
7	Is the reclaimed water used for landscape water requirement	◉ Yes ○ No

Material & Waste Management

	Does these following materials been used in the various building elements	
1	Salvaged timber? Is this material been used	◉ Yes ○ No
2	Glass? Is this material been used	◉ Yes ○ No
3	Gypsum board partitions? Is this material been used	◉ Yes ○ No
4	Ceramic tiles? Is this material been used	◉ Yes ○ No
5	Terrazoo flooring? Is this material been used	◉ Yes ○ No
6	Crushed Stone? Is this material been used	◉ Yes ○ No
7	Recycled aggregate? Is this material been used	◉ Yes ○ No
8	Industrial waste/by-product? Is this material been used	◉ Yes ○ No
	Have the products been extracted, processed and manufactured locally(distance of influence=160km) for the following components(percentage of building component required to meet the criteria=50%	
9	Framing	◉ Yes ○ No
10	Aggregate for concrete and foundation	◉ Yes ○ No
11	Dry wall or interior sheathing	◉ Yes ○ No
12	What is the percentage of reclaimed materials used in constructing the building	20
13	Is the concrete made with minimum 20 percent of supplementary cementitious materials (like fly-ash, slag, metakaolin, rice husk ash, and other pozzolona binder materials and 50% recycled content	◉ Yes ○ No
14	Are the wood products FSC (Forest Stewardship Council) certified	◉ Yes ○ No
15	Is the manufacturer/producer of the various materials directly or indirectly responsible for extended producer responsibility	◉ Yes ○ No
16	Are the multicolored bins provided for waste segregation at source	◉ Yes ○ No
17	Is space provided for hygienic storage of segregated waste	◉ Yes ○ No
18	Is the waste disposal carried out efficiently either on-site or by municipal community	◉ Yes ○ No

Sustainable Sites

1	Does the site consist of prime farmland	◉ Yes ○ No
2	Does the site lie within a flood hazard area	○ Yes ◉ No
3	Is the site near to an area which is home for species listed as threatned or endangered	◉ Yes ○ No
4	Is the site near to an area which is home for species listed as threatned or endangered	◉ Yes ○ No
5	What is the percentage area with shading/non-absorptive material	45
6	Is there a publicly accessible or community based open space that is at least 3/4 acre within 800m radius	◉ Yes ○ No
7	Are there 2 smaller open spaces totalling 3/4 acre	◉ Yes ○ No
8	Is there a publicly available space at the project site	◉ Yes ○ No
9	Do the street lighting luminaries emit any light above 90 degrees (horizintal)	○ Yes ◉ No
10	Is the illumination at property lines zero Footcandles	○ Yes ◉ No
11	Is there uplighting of trees	○ Yes ◉ No
12	Is the top soil suitable for vegetation growth	◉ Yes ○ No
13	Are the fertilizers and manure applied timely to the soil for healthy growth of vegetation	◉ Yes ○ No
14	Is there a good drainage system to avoid water logging	◉ Yes ○ No

Social Welfare

1	Are the product manufacturer's manuals available for all installed equipment, fixtures, appliances, etc.	◉ Yes ○ No
2	Are the residents well aware of efficient use of energy, water and natural resources	◉ Yes ○ No
3	Is the enhanced local exhaust/enhanced whole-house ventilation system installed	◉ Yes ○ No
4	Are there any unvented combustion appliances installed in the building	○ Yes ◉ No
5	Are the floorings water resistant	◉ Yes ○ No
6	Do the floors have enough slopes to drain off the water	◉ Yes ○ No
7	Do the slabs, beams and columns have sufficient cover (as per IS code) to protect the reinforcement from deterioration	○ Yes ◉ No

Health & Wellbeing

1	Is the odour of drinking water objectionable	○ Yes ◉ No
2	Is the turbidity of drinking water between 5 and 10 NTU	◉ Yes ○ No
3	Is the pH of drinking water between 6.5 and 8.5	◉ Yes ○ No
4	Is the total hardness of drinking water between 300 and 600 gm/l of CaCO3	◉ Yes ○ No
5	Is the iron content in the water 0.275 and 0.325 ppm	◉ Yes ○ No
6	Is the Cl content between 250 and 1000ppm	◉ Yes ○ No
7	Is the residual Cl content between 0.2 and 0.5 ppm	◉ Yes ○ No
8	Is the building at least 30 m away from a heavy traffic road	◉ Yes ○ No
9	Do the walls/partitions have a sound reduction index of 40 dB or higher	◉ Yes ○ No
10	Have the earth berms and vegetation been used to curb noise	◉ Yes ○ No
11	Are the doors and windows sound proof	○ Yes ◉ No
12	Are there any heavy noise making appliances	◉ Yes ○ No
13	Is there garbage collection without exposing to open environment	◉ Yes ○ No
14	Is the waste water disposal been carried out on site	◉ Yes ○ No
15	Are any mosquito controlling steps taken	◉ Yes ○ No
16	Are the three processes of separation, containment and destruction followed in human excreta disposal	◉ Yes ○ No
17	Is the rubble disposed off properly without blocking the roads, drainage , etc	◉ Yes ○ No
18	Are all the insulations used in the building free of CFCs and HCFCs	◉ Yes ○ No
19	Are all the HVAC and refrigeration equipments free of CFCs	◉ Yes ○ No
20	Are fire separation systems and fire extinguishers installed in the building free of halon	◉ Yes ○ No

Energy Efficiency

1	What is the total renewable energy produced per year by the system?(in kWh)	24
2	Are the refrigerators BEE qualified	◉ Yes ○ No
3	Are the ceiling fans BEE qualified	◉ Yes ○ No
4	Are the other devices (washing machines, dish washers, etc) BEE qualified	◉ Yes ○ No
5	Is there a meter/sub-meter fo each residential unit instaled	○ Yes ◉ No
6	What is the percentage reduction in energy consumption associated with the interior lighting over baseline power density of 0.48W/Sqft or 5.2 W/sqm	20
7	What is the daylight factor of the building (in percentage)	5
8	Are the vertical transportation systems(elevators, escalators ,etc) are BEE certified	◉ Yes ○ No

Transportation

1	Is the bus stop within 640 m radius	◉ Yes ○ No
2	What is the accessibility of the bus stop (in Kilometers)	5
3	Do the residents use bicycles	○ Full ◉ Partial ○ No use
4	How many amenities are within 800m radius from the building site	10
5	Are the pavements at building site environmental friendly	◉ Yes ○ No
6	Is there an underground/ground-level parking garage	○ Yes ◉ No

Management

1	Is the waste disposed openly in the vicinity of the building	○ Yes ◉ No
2	Are the harmful effluents disposed off to the nearby water bodies	○ Yes ◉ No
3	Are the fuel sources away from the areas vulnerable to fire catching	◉ Yes ○ No
4	Are the fire warning systems (sound alarms, engage sprinklers, etc) installed	◉ Yes ○ No
5	Are there fire emergency exits	◉ Yes ○ No
6	Are fire extinguishers and fire hydrants installed	◉ Yes ○ No
7	Are the polythene products being dumped properly at the building site	◉ Yes ○ No

Submit Reset

7.4 Summary of Phase – IV study

Based on the relative weights of criteria and global weights of attributes, this phase of the work brings out a simple evaluation system for building performance towards sustainability. The developed SBAT framework is integrated with the Internet of Things (IoT) to reach public accessibility quickly and easily. Various open-source software, script language creator and document viewers are utilized to develop a Graphical User Interface (GUI) system. The following are specific conclusions derived from this phase of investigation.

- Based on a 100 point scale, the Sustainable Building Performance Score (SBPS) can be evaluated for a particular building. Further, the study also develops the flexibility to find the preferential based SBPS with respect to four sustainable SEET indicators.
- The study proposed a five-star rating system for SBAT system to categorize sustainable performance of the building.
- A Graphical User Interface (GUI) system is established for the developed SBAT framework, which acts as a self-assessment tool for the users of the building to identify the potential gaps and improvements in attaining a status of sustainable building.
- The study embedded the user-friendly QR code to the developed web portal for the assessment tool to improve awareness and public outreach.
- The sensitivity of the SBAT framework is checked for one of the former green buildings (CII- Godrej at Hyderabad, India) and it was found effective and definite in evaluating the sustainable building performance.
- Although the developed SBAT framework is for the Indian scenario, the methodology remains valid for other developing countries where similar prevailing conditions exist.

Based on conclusions drawn from various phases of work, the overall conclusions and scope for further work is briefed in Chapter 8.

CHAPTER – 8

CONCLUSIONS AND SCOPE FOR FURTHER WORK

8.0 General

The Sustainable Building Assessment Tool (SBAT) is a comprehensive methodology involving qualitative and quantitative methods. The present work incorporates the Technological dimension to rejuvenate the ideas of reuse, recycle, reduce, renew, and regenerate into implementable solutions to the existing Triple-Bottom-Line (TBL). The Social, Environment, Economic and Technological (SEET) indicators are integrated to develop a sustainable building assessment framework for achieving sustainable construction. Considering local context, climate conditions, culture, topography, and ethical aspects prevailing in India, the study emphasized on the suitability of potential and possible criteria to be adopted. The study compared, identified, and evaluated Eight sustainable criteria and 37 sustainable attributes to assess the building performance to develop a Sustainable Building Assessment Tool (SBAT). The Fuzzy Analytical Hierarchy Process (FAHP) is employed to assess the relative weight of indicators, criteria, and attributes and establish the interrelationship among them. A user-friendly Graphical User Interface (GUI) HTML based web page is developed to facilitate the users to assess the building performance. To increase the public outreach QR Code is embedded with the SBAT assessment methodology. Based on a detailed investigation carried out, the following conclusions have been drawn. The same are detailed under different subheadings.

8.1 Conclusions

The study identified the need for promoting and practicing sustainable design and adoption of sustainable principles enabling the transformation from the conventional to sustainable construction in India. The following conclusions are drawn from the present research work

1) Technological dimension has been incorporated in the existing Triple Bottom Line (TBL) approach by introducing the concept of 5R’s (Reduce, Recycle, Reuse, Repair and Renovate).

2) Eight criteria and 37 attributes have been tailored under Social, Environmental, Economic and Technological (SEET) indicators, to adopt to the Indian context considering climatic variations, local context, topography, culture, and heritage.
3) The Technological indicator with a normalized interrelated weight of 28.4% was highest among SEET indicators. Also, under the Technological indicator, the criterion 'Material and Waste Management' has attained the highest interrelated weight of 15.56%.
4) The relative weights of the criteria are obtained from the Eight focused expertise groups comprising of Academicians, Consultants, Contractors, Designers, Engineers, Architects, Suppliers and other stakeholders of the construction industry based on a structured questionnaire on a seven-point Likert scale.
5) The Eight proposed criteria include Water Efficiency (12.63%), Materials and Waste Management (13.96%), Health and Well-being (13.04%), Energy Efficiency (13.15%), Sustainable Sites (12.88%), Social Welfare (11.48%), Transportation (11.36%), and Management (11.49%). These criteria facilitate policymaking, formulate guidelines and develop the green building rating tool.
6) From the findings, it can be observed that the relative weights of indicators are in the order of Environmental (30%), Technological (27%), Economic (22%), and Social (21%). Material and Waste management (MW) and Energy Efficiency (EE) attained the highest relative weights of 14.98% and 13.96% respectively.
7) The criteria, 'Regionally available materials' and 'renewable energy production' attained global weights of 3.01% and 2.40% respectively among the various attributes chosen under Technological indicator.
8) Ten significant factors viz., Climate change, Pollution, Construction & Demolition Waste, resource consumption, life cycle cost, Health & Safety, Local economic development, Recyclability and reusability, Human satisfaction, and Practicability & flexibility were identified to assess the material performance based on content analysis.
9) Three methods (EFTOPSIS, MSPS, and SMPI) were used for assessing the material performance. These methods revealed the significance of adopting material life cycle phases in the selection of sustainable material, without the need for inventory data.

10) It was noted that the method ‘Sustainable Material Performance Index’ (SMPI) was found to be robust and flexible and was able to accommodate both qualitative and quantitative insights. Higher the SMPI value, better is the material performance towards sustainability.
11) Among the five different binder material alternatives (OPC, PPC, PSC, GP, and CC) investigated, it was observed that Geopolymer (GP) is highly prioritized with an SMPI value of 10.63. This was evaluated based on multi Criterion Decision Making (MCDM) methods.
12) The study witnessed the order of significance of the material life cycle as Post-construction (39%), Construction (32%) and Pre-construction (29%), based on analysis of Relative Ranking Index (RRI).
13) Among the 10 identified sustainable factors for material evaluation, the factors ‘Climate change’ and ‘Pollution’ has highest SMPI values in the three life-cycle phases.
14) The SMPI framework developed from the study, facilitates valuable inputs to building professionals in selecting a sustainable material alternative, without the need for Life Cycle Inventory data.
15) The novel method of assessment of building (SBAT), using attribute global weights takes into account, the sensitivity to suit the practices, issues, and priorities of local to a certain region.
16) A scoring system to evaluate the Sustainable Building Performance Score (SPBS) based on the allotted credits points to attributes was developed. Further, a five-star rating based on a number of credit points to categorize sustainable performance of the building, more robust than the existing building assessment tools is evolved.
17) A Graphical User Interface (GUI) embedded with QR code is developed for the end-user and acts as a self-assessment tool to identify the potential gaps and improvements for attaining the status of a sustainable building.

8.2 Significant contribution from the research work

Through the development of the SBAT framework, a new contribution has been made to the literature within this discipline. The most important of these are as follows:

- The well-known existing assessment tools for building assessment tend to avoid explicit disclosure of the process based on which their methods are developed. This study not only proposes a theoretical model but also makes the methodology transparent.
- The basis of any building assessment method is embedded in its assessment indicators, criteria, attributes and prerequisites. The present study highlights disclosed the applicable criteria and attributes that form the main structure specific to Indian sustainable building assessment.
- Weighting systems are integral to reliable evaluation. This study has determined a weighting system for the approved criteria and attributes, which form the most applicable framework for the sustainable development of the built environment in India. The weighting system developed, includes a procedure (weights, interrelations, rating formulas, benchmarking expression and categorization) that provides a single result to indicate the level of sustainability of built environment.
- In terms of impact on the community, the framework can potentially act as an education medium that encourages a continuous learning process, enhances communication between, stakeholders and Architects, Designers, Consultants, Engineers, Contractors, Suppliers, and Academicians. The framework developed could potentially be used as a guideline for planning or policymaking to promote sustainable buildings in India. It is hoped that in this manner, the theoretical model becomes more flexible and consequently more adaptable, for other developing countries also.

More broadly, the Sustainable Building Assessment Tool (SBAT) contributes to the development of a new model or approach particularly appropriate to developing countries, and through which a country-specific building sustainability assessment framework can be established.

8.3 Scope for further work

The scope for future work can include the following:

1) The input choice for building assessment can be improved instead of only Yes/No questionnaire.
2) The simulation models can be embedded to increase the viability of the tool.
3) Additional criteria and attributes can also be included to broaden the scope to recent advances in evaluation of sustainability.
4) A database consisting of a number of case studies for various buildings assisting the local authorities in achieving sustainable construction can be created.

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JOURNAL PAPERS /BOOK CHAPTERS – Under Review

1) **Suchith Reddy Arukala**, Rathish Kumar. & P, Anand Raj. P. "Quantifying Interdependency between Sustainable Criteria and Indicators for developing a building assessment tool, **Journal of Construction Engineering and Management, ASCE publications** (Under Review)
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Appendix A: Delphi Survey

(This survey was sent to various experts in the construction industry)

Dear Expert,

A research study is being conducted to develop sustainable building assessment tool for developing countries like India. Various sustainable attributes are listed out from well-known assessment tools like LEED, BREEAM, GRIHA and IGBC. To reach a consensus decision for selecting the most significant attributes, the Delphi Technique is employed. Delphi technique involves brainstorming, revising, narrowing and rating of the attribute for a number of iterations. Therefore, it is requested to carefully analyze and give the response.

Personal Information

Name:

Organization:

E mail id:

Please indicate the level of significance of each sustainable attribute on a scale of 1 to 5 in the Table below.

Keeping in view the unique local context, climate conditions, culture, topography, and ethical aspects prevailing in India, the most prominent and potential sustainable attributes have been compiled from existing tools (BREEAM, LEED, IGBC, and GRIHA), policies and guidelines. Please indicate the level of significance of each sustainable attribute on a scale of 1 to 5 for the Indian built environment.						
Sl. No	**Attributes**	**Very low Important (1)**	**Low Important (2)**	**Moderate Important (3)**	**High Important (4)**	**Very High Important (5)**
1	Water monitoring and leak detection (SC1)					
2	Building water use reduction (SC2)					
3	Recycling of water (SC3)					
4	Reuse of water (SC4)					
5	Grey water recycling (SC5)					
6	Rainwater management (SC6)					
7	Reduction in Landscape water requirement (SC7)					

Sl. No	Attributes	Very low Importan t (1)	Low Important (2)	Moderate Important (3)	High Important (4)	Very High Important (5)
8	Low-energy materials (SC8)					
9	High-performance material (SC9)					
10	Material replacement (SC10)					
11	Regionally available materials (SC11)					
12	Recycled and reuse of materials (SC12)					
13	Material Efficiency (SC13)					
14	Energy Efficiency (SC14)					
15	Use of salvaged, refurbished material (SC15)					
16	Responsible sourcing (SC16)					
17	Efficient waste management (SC17)					
18	Visual and thermal comfort (SC18)					
19	Indoor air quality (SC19)					
20	Ventilation (SC20)					
21	Lighting (SC21)					
22	Thermal comfort (SC22)					
23	Water quality & water pollution (SC23)					
24	Outdoor & indoor noise levels (SC24)					
25	Reduce air pollution (SC25)					
26	Sanitation/Safety facilities & Accessibility (SC26)					
27	Habitant Satisfaction (SC27)					
28	Minimize ozone depletion (SC28)					
29	Renewable energy production (SC29)					
30	Energy efficient appliances (SC30)					
31	Energy monitoring (SC31)					
32	Reduction in energy consumption associated with interior lighting (SC32)					

Sl. No	Attributes	Very low Importan t (1)	Low Important (2)	Moderate Important (3)	High Important (4)	Very High Important (5)
33	Adequate lighting (SC33)					
34	Refrigerant management/Green power (SC34)					
35	Solar water heating (SC35)					
36	Optimize energy performance (SC36)					
37	Energy Efficient Vertical transportation systems (SC37)					
38	Site selection (SC38)					
39	Protect or restore habitat (SC39)					
40	Heat island reduction (SC40)					
41	Open space (SC41)					
42	Reduced light pollution (SC42)					
43	Conservation of soil surrounding the building (SC43)					
44	Storm water design (SC44)					
45	Site improvement plan (SC45)					
46	Protect ecosystem and preserve biodiversity (SC46)					
47	Knowledge and Awareness towards sustainability (SC47)					
48	Local Economic Development (SC48)					
49	Development of Skill (SC49)					
50	Employment opportunities (SC50)					
51	Efficient ventilation (SC51)					
52	Design for durability (SC52)					
53	Protect cultural heritage (SC53)					
54	Public transport accessibility (SC54)					
55	Use of Bicycles (SC55)					
56	Proximity to amenities (SC56)					

Sl. No	Attributes	Very low Important (1)	Low Important (2)	Moderate Important (3)	High Important (4)	Very High Important (5)
57	Environmentally friendly pavements at the building site (SC57)					
58	Use of solar power vehicles (SC58)					
59	Innovation in transportation (SC59)					
60	Reduced parking footprint (SC60)					
61	Managing the balance between the building and its immediate surrounding (SC61)					
62	Managing fire prevention facilities (SC62)					
63	Life cycle costing (SC63)					
64	Integrated design process (SC64)					
65	Responsible construction practices (SC65)					
66	Construction site improvements (SC66)					
67	Preventing the reckless dumping of polythene products at the building site (SC67)					
68	Stakeholder participation (SC68)					

Please list further attributes which are not covered above, if any, that may be consider important for Indian built environment.

1.

2.

3.

Appendix B: Survey Response
(Importance of Criteria with respect to Indicators)

The questionnaire survey is designed and formulated to observe the importance of each of the identified criteria with respect to four indicators (i.e., Social, Environment, Economic and Technological)

	Economic								Environmental								Social								Technological							
	WE	MW	HW	EE	SS	SW	T	M	WE	MW	HW	EE	SS	SW	T	M	WE	MW	HW	EE	SS	SW	T	M	WE	MW	HW	EE	SS	SW	T	M
R1	3	4	4	5	3	6	4	7	7	7	7	7	6	7	7	4	6	7	7	6	7	3	6	4	4	4	6	7	5	6	5	6
R2	4	3	3	3	5	5	3	3	4	4	4	4	4	4	4	4	5	5	5	4	3	3	4	4	6	6	4	4	3	3	4	4
R3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
R4	5	5	5	5	5	5	5	5	7	7	7	7	7	7	5	7	5	5	5	5	5	5	5	5	7	5	5	5	5	5	5	5
R5	2	4	5	6	3	1	4	6	6	6	6	7	4	4	5	6	5	6	4	6	5	6	5	6	7	7	5	7	5	6	6	7
R6	5	5	4	5	7	5	5	6	7	7	6	6	7	6	6	7	6	5	5	6	7	5	6	7	6	6	6	7	7	6	7	7
R7	4	5	4	4	6	5	6	6	6	7	4	5	6	5	7	4	4	3	4	5	6	5	6	4	2	3	4	4	4	5	5	5
R8	5	5	6	6	6	5	5	6	6	5	5	5	6	6	6	5	5	6	5	5	6	6	6	5	6	5	6	5	6	6	5	4
R9	1	4	7	4	6	7	3	7	4	7	7	7	5	7	7	4	4	7	7	6	4	5	5	7	4	7	5	7	6	7	5	6
R10	7	7	7	7	7	4	4	7	7	7	7	7	7	7	7	4	7	7	7	7	7	7	7	4	7	7	7	7	7	7	7	6
R11	5	7	7	7	6	7	6	7	7	7	7	7	4	7	7	6	7	7	7	7	6	7	6	7	7	7	7	7	6	7	6	7
R12	6	5	7	7	5	6	6	7	7	7	7	7	6	7	7	5	6	6	6	6	7	6	6	6	6	6	6	6	6	6	6	5
R13	4	6	7	4	4	7	5	6	7	7	7	7	6	7	7	5	7	7	7	7	5	7	7	5	7	7	7	7	6	7	7	6
R14	5	5	7	7	5	7	5	7	7	7	7	7	7	7	7	4	7	7	7	5	7	7	7	7	7	5	6	7	7	7	7	7
R15	5	7	6	6	6	6	6	6	6	7	6	6	6	6	6	6	5	7	6	6	6	6	6	6	5	7	6	6	6	6	6	6
R16	5	5	6	7	5	6	5	7	6	7	7	7	7	7	7	5	5	6	6	6	6	5	5	5	4	5	5	5	5	5	4	6
R17	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
R18	6	6	6	7	6	7	6	7	7	7	7	7	6	7	7	6	6	7	7	7	7	6	7	6	7	7	6	7	6	7	6	7
R19	6	3	2	4	4	2	2	3	5	4	2	4	5	2	3	3	3	3	2	3	4	2	3	3	6	4	3	4	5	2	3	4
R20	2	3	5	5	5	6	4	7	6	7	6	7	6	7	6	4	7	7	5	5	5	5	4	4	7	5	5	7	7	6	4	6
R21	4	7	7	7	7	7	7	7	7	7	7	7	1	7	7	6	5	7	7	4	4	7	7	4	7	7	7	7	7	7	7	7
R22	5	2	4	2	4	7	7	7	7	7	7	7	4	7	7	7	2	4	5	5	5	5	5	7	4	3	4	4	3	5	4	7
R23	2	6	5	4	4	6	6	7	7	7	4	5	5	7	5	6	6	6	5	3	3	6	6	5	5	5	3	4	3	5	6	6
R24	4	7	7	7	4	5	5	7	7	7	7	7	4	7	7	5	5	7	7	7	7	5	7	5	7	7	6	7	5	7	7	7
R25	5	6	5	7	6	5	6	6	6	7	4	7	6	5	6	6	7	7	5	7	6	5	6	7	5	6	5	7	6	6	6	6
R26	4	4	3	3	4	6	6	4	3	3	5	5	6	5	5	6	2	5	3	6	6	5	6	7	6	4	6	4	6	6	4	5
R27	6	6	7	7	7	7	4	7	7	7	7	7	7	7	6	1	6	7	6	7	7	6	7	6	7	7	7	7	7	7	6	7

R28	5	7	5	5	7	6	6	6	7	7	7	7	6	7	7	1	3	3	6	5	6	6	5	5	7	7	7	6	7	7	1	4
R29	5	7	5	5	4	7	6	7	6	7	6	7	5	7	6	5	6	7	5	7	5	5	5	7	7	7	6	7	7	7	6	6
R30	6	6	4	4	6	4	6	5	6	6	4	4	6	4	6	5	6	6	4	4	6	4	6	5	6	6	4	4	6	4	6	5
R31	3	4	6	7	4	7	5	7	7	7	7	7	5	7	7	5	7	7	7	6	7	7	7	7	3	5	6	6	6	7	7	6
R32	6	5	5	6	6	6	6	6	7	7	6	6	6	6	7	6	6	6	7	6	6	6	6	6	6	6	6	7	7	7	6	7
R33	4	1	4	7	4	1	1	1	7	7	7	7	7	6	7	7	7	7	7	7	7	6	7	7	6	6	6	7	7	6	7	7
R34	7	7	7	7	7	7	7	7	7	7	6	6	6	6	7	7	5	6	7	7	6	6	7	7	7	7	7	7	6	6	7	7
R35	2	2	3	7	6	5	6	7	7	6	7	7	7	6	7	7	6	7	6	7	6	6	7	7	3	5	4	7	6	6	6	7
R36	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
R37	6	7	6	7	7	5	6	7	6	7	7	7	7	6	7	6	6	7	7	7	7	7	7	6	6	7	4	7	6	7	6	7
R38	6	3	7	7	7	7	6	7	7	7	7	7	7	7	7	7	4	6	7	7	7	7	7	7	6	7	7	7	7	7	7	7
R39	3	5	5	6	5	6	4	7	6	7	7	6	5	6	6	4	4	5	6	4	6	5	4	5	4	5	5	6	5	7	3	6
R40	3	1	6	1	3	1	5	4	5	5	6	7	3	2	4	3	3	6	5	6	3	2	7	3	4	4	7	4	1	7	6	7
R41	4	3	4	4	4	4	4	6	4	2	4	4	4	3	3	5	4	4	4	4	3	3	3	5	4	4	4	4	4	4	4	5
R42	5	5	6	7	6	6	5	6	7	7	6	7	7	6	6	5	6	7	6	5	5	5	5	5	6	6	7	6	6	6	5	5
R43	5	6	5	5	4	7	5	7	7	7	7	7	4	5	7	4	3	6	6	3	7	3	6	6	6	5	5	4	6	6	3	6
R44	4	5	4	5	5	6	6	5	5	5	6	3	6	6	6	5	5	5	2	4	5	5	5	5	5	5	2	4	5	5	5	5
R45	4	5	7	7	6	7	7	6	4	5	7	7	7	7	7	7	7	5	7	7	6	7	7	6	7	5	7	7	7	7	7	7
R46	5	4	5	5	4	3	4	5	4	3	4	5	4	3	4	4	4	3	4	5	4	3	5	4	4	4	4	5	4	3	4	4
R47	7	5	7	7	5	7	5	7	7	7	7	7	7	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	6	7	5	7
R48	5	5	6	6	6	7	4	7	7	7	7	7	7	7	6	3	6	6	7	5	7	7	6	6	5	4	4	6	6	6	3	6
R49	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	2	7	7	5	6	7	7	7	7	6	7	7	7	7	7	7	6
R50	4	6	4	5	2	2	3	4	6	7	6	6	4	6	4	5	4	6	6	4	3	5	5	6	5	5	5	7	6	6	6	6
R51	7	4	4	6	5	6	4	7	6	6	6	7	6	7	5	7	6	7	6	7	3	6	3	7	6	6	6	5	6	7	6	7
R52	6	7	7	5	7	5	5	4	7	7	7	5	6	6	5	4	6	7	7	5	6	6	5	4	7	7	7	4	6	5	5	3
R53	4	5	6	3	4	6	7	3	7	7	7	4	3	7	7	6	6	7	5	4	5	7	7	6	5	7	6	7	4	6	5	5
R54	1	7	5	6	7	5	6	7	2	7	5	6	7	7	4	7	1	5	5	6	7	7	5	7	1	5	5	6	7	4	5	7
R55	6	6	6	6	6	7	7	7	7	7	7	5	7	7	7	6	7	5	6	5	6	6	7	6	7	7	7	7	7	7	7	6
R56	4	1	5	6	4	5	4	6	6	7	6	6	4	7	6	3	6	5	6	5	6	4	4	5	6	4	4	7	4	5	5	3
R57	5	5	4	4	5	4	4	5	4	5	4	4	5	4	4	5	4	5	4	4	5	4	4	5	4	5	4	4	5	4	4	5
R58	6	5	6	5	6	5	6	5	6	6	5	6	6	6	6	5	5	5	6	6	6	5	6	5	6	6	6	6	6	5	6	5

Appendix C: Questionnaire Survey

(Importance of Attribute corresponding to criteria)

Based on the identified criteria and attribute, a structured questionnaire survey is prepared in such a way that the importance of each of these attribute corresponding to their criterion is evaluated. The level of significance of each the attribute performance corresponding to their criterion is rated by 34 respondents on a five point Likert scale.

Criteria	Attribute	Respondents																																	
		R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34
WE	A1	4	3	3	5	5	4	4	5	4	5	4	3	4	5	4	5	4	3	5	4	4	5	4	3	3	3	3	3	3	3	3	3	5	5
	A2	3	4	1	4	4	1	4	3	5	4	2	3	4	4	5	4	2	3	4	2	5	4	2	3	4	4	1	4	4	1	4	2	4	4
	A3	5	5	3	5	4	5	3	4	4	3	4	4	3	4	4	3	4	4	3	4	4	3	4	4	5	5	3	5	5	3	5	3	5	4
	A4	4	5	2	5	4	5	4	5	3	4	5	4	3	4	3	4	5	4	4	5	3	4	5	4	5	5	2	5	5	2	5	2	5	4
	A5	3	3	1	4	4	4	3	3	3	4	3	3	4	4	3	4	3	3	4	3	3	4	3	3	3	3	1	3	3	1	3	2	4	4
MW	B1	4	3	2	3	3	3	3	2	5	4	3	2	2	3	5	4	3	2	4	3	5	4	3	2	3	3	2	3	3	2	3	2	3	3
	B2	3	5	1	5	5	4	4	5	4	3	4	4	4	5	4	3	4	4	3	4	4	3	4	4	5	5	1	5	5	1	5	3	5	5
	B3	4	3	2	4	4	5	1	4	4	4	5	4	4	4	4	4	5	4	4	5	4	4	5	4	3	3	2	3	3	2	3	2	4	4
	B4	4	5	1	4	4	4	3	4	3	3	3	4	5	4	3	3	3	4	3	3	3	3	3	4	5	5	1	5	5	5	5	4	4	4
	B5	5	4	2	5	5	5	3	4	3	2	5	5	2	5	3	2	5	5	2	5	3	2	5	5	4	4	2	4	4	2	4	2	5	5
HW	C1	4	4	2	5	5	3	5	3	4	3	3	3	4	5	4	3	3	3	3	3	4	3	3	3	4	4	2	4	4	2	4	2	5	5
	C2	5	4	2	4	4	2	4	2	3	4	3	4	4	4	3	4	3	4	4	3	3	4	3	4	4	4	2	4	4	2	4	2	4	4
	C3	4	4	2	5	5	3	4	4	4	3	4	3	3	5	4	3	4	3	3	4	4	3	4	3	4	4	2	4	4	2	4	2	5	5
	C4	5	2	2	5	4	2	5	3	5	3	2	4	3	4	5	3	2	4	3	2	5	3	2	4	2	2	2	2	2	2	2	2	5	4
EE	D1	4	5	4	4	3	4	4	3	4	5	4	4	4	3	4	5	4	4	5	4	4	5	4	4	5	5	4	5	5	4	5	4	4	3
	D2	4	4	3	4	4	4	4	3	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	3	4	4	3	4	3	4	4

	D3	3	3	4	4	5	3	5	3	3	2	3	3	5	5	3	2	3	3	2	3	3	2	3	3	3	3	4	3	3	4	3	4	4	5
	D4	4	2	2	5	5	4	1	4	3	1	2	5	4	5	3	1	2	5	1	2	3	1	2	5	2	2	2	2	2	2	2	2	5	5
	D5	4	4	5	5	5	5	3	3	5	4	3	2	5	5	5	4	3	2	4	3	5	4	3	2	4	4	5	4	4	5	4	5	5	5
	D6	4	2	3	4	5	5	4	4	4	3	5	4	3	5	4	3	5	4	3	5	4	3	5	4	2	2	3	2	2	3	2	3	4	5
SS	E1	5	3	4	3	5	5	5	4	5	4	5	4	5	5	5	4	5	4	4	5	5	4	5	4	3	3	4	3	3	4	3	4	3	5
	E2	5	4	5	4	4	4	4	3	4	5	4	3	5	4	4	5	4	3	5	4	4	5	4	3	4	4	5	4	4	5	4	5	4	4
	E3	3	3	2	5	4	4	4	4	5	5	4	3	4	4	5	5	4	3	5	4	5	5	4	3	3	3	2	3	3	2	3	2	5	4
	E4	5	4	4	5	5	5	4	3	2	1	5	3	2	5	2	1	5	3	1	5	2	1	5	3	4	4	4	4	4	4	4	4	5	5
	E5	4	3	3	4	5	4	4	4	2	3	4	5	4	5	2	3	4	5	3	4	2	3	4	5	3	3	3	3	3	3	3	3	4	5
	E6	5	5	4	5	5	5	4	4	3	4	5	4	5	5	3	4	5	4	4	5	3	4	5	4	5	5	4	5	5	4	5	4	5	5
SW	F1	4	3	5	4	4	4	4	3	5	4	3	4	3	4	5	4	3	4	4	3	5	4	3	4	3	3	5	3	3	5	3	5	4	4
	F2	5	4	3	4	4	5	5	4	3	4	4	3	4	4	3	4	4	3	4	4	3	4	4	3	4	4	3	4	4	3	4	3	4	4
	F3	5	4	4	4	5	5	5	4	4	4	5	4	4	5	4	4	5	4	4	5	4	4	5	4	4	4	4	4	4	4	4	4	4	5
T	G1	4	5	5	3	4	5	4	4	3	4	4	3	5	4	3	4	4	3	4	4	3	4	4	3	5	5	5	5	5	5	5	5	3	4
	G2	4	3	4	5	4	5	4	4	3	4	4	3	5	4	3	4	4	3	4	4	3	4	4	3	3	3	4	3	3	4	3	4	5	4
	G3	3	5	2	4	4	4	5	4	4	3	5	2	3	4	4	3	5	2	3	5	4	3	5	2	5	5	2	5	5	2	5	2	4	4
	G4	3	2	1	5	5	5	4	4	5	4	5	4	5	5	5	4	5	4	4	5	5	4	5	4	2	2	1	2	2	1	2	1	5	5
	G5	5	2	4	3	4	4	4	3	2	3	4	3	2	4	2	3	4	3	3	4	2	3	4	3	2	2	4	2	2	4	2	4	3	4
M	H1	4	4	5	4	5	1	4	4	3	4	5	4	3	5	1	4	4	3	4	5	4	3	1	1	4	1	4	4	1	4	3	3	4	3
	H2	4	3	2	5	5	2	4	4	5	4	4	2	3	5	2	4	4	5	4	4	2	3	2	2	4	2	4	4	2	2	3	5	2	3
	H3	4	3	2	5	4	5	5	4	5	5	5	4	5	4	5	5	4	5	5	5	4	5	5	5	5	5	5	4	5	4	5	5	4	5

Appendix D: Questionnaire Survey

(To evaluate Material Performance w.r.t Sustainable factors)

To evaluate the material performance with respect to each sustainable factors a survey has been taken up. Keeping in view, the material lifecycle thinking, the data is obtained from the respondents. Here ‘1' represents less important and, ‘7' represents high importance.

Note: Binder Material Alternatives- A1-Ordinary Poland Cement (OPC), A2-Pozzolanic Portland Cement Fly ash based (PPC-F), A3- Pozzolanic Portland Cement Slag based (PPC-S), A4- Geopolymer (GP) and A5-Composite Cement (CC).
Sustainable Factors: F1- Climate Change; F2 – Pollution and Emission; F3 – Construction and Demolition waste; F4 – Consumption of resource; F5 – Life cycle cost; F6 – Recyclability and Reusability; F7 – Local Development; F8- Health and Safety; F9 – Practicability and Flexibiliy; F10 – Human Satisfaction

		Respondents																																																			
	Alternat	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31	R32	R33	R34	R35	R36	R37	R38	R39	R40	R41	R42	R43	R44	R45	R46	R47	R48	R49	R50	R51	R52	R53	R54
F1	A1	3	5	3	1	1	2	4	6	3	2	4	1	5	3	3	2	1	4	3	3	4	3	2	3	1	3	2	3	3	2	3	2	2	3	3	2	3	3	2	3	2	4	4	3	3	4	3	3	3	2	3	4	2	4
	A2	3	5	2	2	3	3	3	5	3	4	4	1	5	4	4	4	3	4	4	4	4	5	4	4	4	5	5	5	5	6	5	4	5	4	4	3	5	5	3	4	6	7	6	4	4	3	4	5	5	3	4	5	1	4
	A3	3	6	3	3	4	4	3	5	3	4	4	1	5	4	4	4	4	4	4	5	3	5	4	5	4	5	5	5	5	6	5	4	5	4	4	3	5	5	3	4	6	6	5	4	4	4	5	5	6	3	4	5	1	4
	A4	3	6	2	3	5	6	5	5	3	4	4	1	6	4	4	5	4	5	4	6	3	6	5	5	6	6	6	6	6	7	6	5	5	4	5	4	6	7	5	5	6	7	4	4	6	4	7	5	6	4	5	6	5	4
	A5	3	6	3	3	4	6	4	5	3	4	4	1	5	4	4	5	5	5	3	6	5	5	4	5	4	5	5	5	5	6	6	5	5	5	5	3	6	5	4	5	5	6	5	4	6	3	5	4	6	4	5	5	4	3
F2	A1	3	4	3	1	1	4	4	4	3	3	4	1	5	3	3	2	2	4	4	5	3	3	2	3	2	3	4	3	3	3	4	1	2	2	3	3	4	2	2	3	3	3	4	3	4	3	2	3	4	4	4	4	2	5
	A2	3	4	2	2	4	3	4	3	3	4	4	1	5	4	4	4	3	4	3	6	3	4	3	4	4	4	4	3	4	3	4	2	3	3	4	5	6	3	3	4	3	4	6	4	3	3	3	4	6	5	4	5	2	6
	A3	3	4	3	3	4	4	4	4	3	4	4	1	5	4	3	4	3	4	5	6	3	4	3	4	4	4	4	3	4	4	4	2	3	3	4	5	6	3	3	4	3	4	5	4	3	2	3	4	6	5	4	5	2	4
	A4	3	5	2	3	5	6	4	5	3	4	4	1	5	4	3	6	4	4	3	6	3	5	5	5	4	6	6	5	5	6	6	3	4	4	6	6	7	5	4	6	6	6	5	5	5	4	6	5	7	5	4	7	3	4
	A5	3	5	3	3	5	6	4	4	3	4	4	1	5	4	4	4	3	5	2	6	3	5	4	5	4	4	5	4	5	5	5	3	4	3	5	5	7	4	4	5	4	4	5	4	4	3	4	4	6	5	4	4	3	4
F3	A1	3	7	3	2	1	5	4	6	3	2	4	1	4	3	3	3	3	3	3	7	3	5	4	5	5	4	4	5	5	4	4	4	4	4	4	3	4	3	3	4	4	4	4	3	3	3	4	5	5	6	2	4	3	5
	A2	3	7	2	3	3	4	4	6	3	3	4	1	4	3	3	6	3	3	2	7	2	6	5	5	5	5	5	5	6	4	5	5	5	5	6	5	6	5	6	6	6	6	7	6	3	3	4	6	6	6	3	4	3	5
	A3	3	7	3	3	3	3	4	6	3	4	4	1	4	3	5	4	3	3	3	7	3	6	5	5	5	5	5	5	6	4	5	5	5	5	6	5	6	5	6	6	6	6	6	5	3	5	4	6	7	6	3	4	3	5

	A4	3	7	2	3	3	4	4	6	3	3	4	1	4	3	4	6	4	3	2	7	3	6	5	5	5	5	4	5	6	5	5	5	6	6	7	6	6	6	6	6	6	5	5	4	5	5	5	5	7	6	3	5	4	4
	A5	3	7	3	3	2	5	4	6	3	4	4	1	4	3	4	6	4	3	3	7	3	5	4	5	5	5	4	5	5	4	4	5	5	5	6	5	5	5	6	6	6	6	6	4	4	4	4	5	7	6	3	4	3	4
F4	A1	3	2	2	2	1	2	4	5	2	2	4	1	3	2	3	1	1	3	3	3	2	3	2	2	3	4	3	2	3	2	1	1	2	2	3	1	3	3	2	3	2	3	2	1	2	2	3	3	3	4	4	2	2	4
	A2	3	3	2	2	5	4	4	6	3	3	4	1	3	3	4	4	4	3	3	4	3	4	3	3	3	4	4	3	3	6	3	3	3	4	4	3	4	5	3	4	4	5	3	3	3	4	4	3	4	4	3	3	2	4
	A3	3	3	3	3	5	4	4	5	3	3	4	1	4	3	4	3	4	3	3	4	3	4	3	3	3	4	4	3	3	6	3	3	3	4	4	3	4	5	3	4	4	4	3	2	3	4	4	3	4	4	3	3	2	3
	A4	3	3	2	3	4	5	4	5	3	3	4	1	3	3	4	3	5	3	3	5	3	5	4	5	5	3	5	5	5	5	4	4	5	5	5	5	5	5	4	5	3	4	4	3	4	3	5	5	3	5	2	5	3	3
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