Investigation of key criteria influencing the sustainability of residential buildings in tropical climate

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Abstract. Introduction: The need for sustainable cities and societies is well established and it is recognized as one of the 17 Sustainable Development Goals (SDGs). Sustainable buildings are the key elements in the fabric of sustainable cities. The efforts made in the building sector to accomplish the SDGs is widely accepted in the form of building rating systems and assessment systems, primarily focusing the environmental dimension, but the social and economic dimensions have gained less attention. In this context, developing countries are accustomed to many studies incorporating the three dimensions of sustainability. However, region-specific assessment systems and studies hardly exist especially in a country like India with diverse climatic conditions. Therefore, this study aims to investigate the key criteria influencing the environmental, social and economic sustainability with specific focus to residential buildings in the tropical climatic region of India. Methods: A comprehensive review of the existing Green Building Rating Systems (GBRS) and published literature was performed to establish the initial pool of criteria. Additionally, a questionnaire survey was conducted among experts from various domains to record the importance of each criterion towards sustainability of residential buildings in the tropical climate. The data collected through the questionnaire survey was analyzed and the degree of importance of each criterion was derived using Fuzzy TOPSIS. Further, Pareto analysis was used to arrive at the key criteria. Results: This study has evaluated the importance of each criterion towards sustainability and has proposed a comprehensive framework for assessing the sustainability of residential buildings in tropical climate incorporating the three dimensions of sustainability. The proposed framework would help the state and national governments to streamline the activities in the building sector towards achieving sustainability. Conclusions: The study concludes that a combination of Fuzzy TOPSIS and Pareto analysis is an effective method to define key criteria influencing sustainability. The findings of this study can be helpful to practitioners, researchers and academicians to achieve building sustainability in the tropical climate.

1. Introduction

The building sector is one of the major contributors to sustainable development, and its importance in encouraging environmental, social and economic sustainability is undeniable [1]. Sustainable buildings are the most pronounced elements of sustainable cities. The imperative for sustainable cities is recognized as one of the seventeen Sustainable Development Goals (SDGs). The efforts made in the building sector to accomplish the SDGs is widely acknowledged in the form of building rating/assessment systems [2]. Building rating/assessment systems that exist globally and nationally, bring together sustainable construction practices and solutions to achieve the SDGs put forth by the
United Nations [3]. The global building assessment systems include LEED, BREEAM, CASBEE and many more. India being a developing economy has extreme motives towards sustainability. The Indian Green Building Council (IGBC) devised a rating system for assessing the sustainability of buildings in the Indian context in 2006 highly influenced by the LEED rating system. The Energy and Resources Institute (TERI), with support from the Ministry of New and Renewable Energy (MNRE), Government of India, has developed Green Rating for Integrated Habitat Assessment (GRIHA), which was adopted as the national rating system by the Government of India in 2007. Even though several systems exist, much criticism has been levied on these systems for not accounting sustainability holistically and for not addressing the regional issues and goals [2], [4]. Due to global variations in climate, geography, economics, culture, government policies, regulations and historical context, assessment systems developed for one region might not apply to others [5].

In this context, both developing and developed economies are accustomed to many studies incorporating all the three basic dimensions of sustainability and focusing on multiple SDGs. An initial step in developing assessment systems is to establish the key sustainability criteria. A few studies have contributed to the residential sustainability criteria in the global context [6]–[8]. There are many country-specific contributions in developing sustainability assessment criteria for residential buildings; among them include studies done in the context of Korea [9], Jordan [10], Slovenia [11], Portugal [12], Trinidad and Tobago [13]–[17], Iran [18], China [19], India [20] Baltic states [21], [22] and Pakistan [23]. Most of these countries are having diverse climatic conditions and varied regional requirements. However, hardly few studies exist which explore the region-specific issues, which include studies conducted by Gou and Lau [24], Amin Hosseini et al. [25], Raut et al. [26] and Vyas and Jha [2]. Previous studies reveal the limitations of existing systems in addressing region-specific requirements [27] and necessitates customization of existing systems for specific occupancies addressing the climatic and regional variations [1]. However, region-specific assessment systems and studies hardly exist especially in a country like India with diverse climatic conditions. According to Koppen climate classification, India covers 23 different types of climatic regions [28]. There is a need for developing region-specific assessment systems by determining sustainability criteria uniquely for different climatic regions instead of a single system for the entire country.

Therefore, this study aims to investigate the key criteria influencing the environmental, social and economic sustainability with specific focus to residential buildings in the tropical climatic region of India. The current study tends to answer the following research questions: 1) What are the key factors influencing the sustainability of residential buildings in the tropical climatic region of India? 2) What is the perception of stakeholders in the tropical climatic region about the sustainability of residential buildings? The answers to these research questions would help to sense the critical criteria. It is assumed that this study would add significant value to the body of knowledge on building rating systems and assessment systems.

2. Methodology

2.1. Phase I: Identification of criteria

Most of the authors have relied upon the building rating systems and previous literature for the identification of criteria. The preliminary list of criteria is identified based on reviewing the following: 1) the most studied rating systems [29] like LEED, BREEAM, CASBEE, SBTool, DGNB along with CSH and HQM; 2) the rating systems existing in tropical countries like GBI, LOTUS, BERDE and rating systems from India like IGBC rating system and GRIHA; 3) the published literature which had established the key sustainability criteria for residential buildings [7], [8], [18]–[26], [10]–[17]. The preliminary list of criteria is refined through content analysis by eliminating the repetitive and irrelevant criteria to tropical climates. Also, a structured interview of experts in the building industry is conducted.

The identified criteria are then classified under different categories and sustainability dimensions with reference to the classification adopted by rating systems and previous literature.
2.2. Phase II: Data collection through questionnaire survey
The criteria identified need to be prioritized based on expert opinion to arrive at the critical criteria. The process involves various tasks such as identification of suitable methods for prioritization, preparation of questionnaire for recording expert opinion, selection of experts and conducting the questionnaire survey. Choosing an appropriate prioritizing method is a challenging task [30]. While selecting a prioritization method for arriving at the critical criteria the following aspects are thought of; 1) ability to account for uncertainty in expert judgements; 2) ability to arrive at degree of importance of each criterion; 3) ability to check for inconsistent judgements; 4) ability for group decision making; 5) ability to handle large pool of criteria. Multi-Criteria Decision Making (MCDM) methods are recognized as the most widely used method for prioritization of sustainability criteria [31]. Analytical Hierarchy Process (AHP) is proven as the most suited MCDM method for prioritization of sustainability criteria considering its transparency, group decision making characteristics for arriving at priority weight and capability for checking inconsistent judgements [30]. However, AHP fails to accommodate the uncertainties in expert judgements [32] and has limitations in handling a large pool of criteria because of the pairwise comparisons involved [30]. Even though combining AHP and Fuzzy approach takes care of the uncertainties in expert judgements [33], it is difficult to handle a large pool of criteria. The direct rating of criteria on a Likert scale is identified as a practical solution and Fuzzy TOPSIS as a suitable method to analyze the collected data.

The prioritization of criteria is done based on the perception of experts in the building industry with the aid of a questionnaire survey. Depending on the prioritization method selected the questionnaire is prepared. The questionnaire is designed with three sections, which include a brief introduction to the objectives of the questionnaire survey, few questions to record the details of the experts and also questions to record the perception of experts on the importance of each criterion on the Likert scale. The number of scale points to be included is a crucial decision to be made. According to Cronbach and Fabrigar [34], the optimal scale length fall between 5 - 7. The current study records the perception of experts using a 7-point scale ranging from 1 (extremely low importance) to 7 (extremely high importance). Since the resulting priority of the identified criteria solely depends on the perception of the experts, they need to be wisely selected. The decision-making process in the sustainable building sector shall involve the participation of experts from various domains and should not be limited to any particular group of experts. Literature also highlights the importance of expert involvement in the development of assessment systems [35]. Therefore, experts with at least 15 years of professional experience in the building industry are selected from various domains. The experts include: 1) project manager with 27 years of experience; 2) services manager with 24 years of experience; 3) procurement manager with 26 years of experience; 4) Building design consultant with 26 years of experience; 5) Sustainable design consultant with 15 years of experience; 6) Academician with expertise in sustainable buildings with 20 years of experience; 7) Environmental consultant with 20 years of experience; 8) Energy expert with 25 years of experience. The respondents were selected through judgemental sampling. The questionnaire was pretested among limited experts with specific objectives which include 1) to test the general layout and interface of the questionnaire; 2) to have an idea on the approximate time required to complete the survey; 3) to identify, any critical modifications required on the questionnaire. Further, the questionnaire is refined and administered.

2.3. Phase III: Data analysis
The data matrix prepared from the data collected through the questionnaire survey is analyzed to arrive at the degree of importance of the sustainability criteria and to establish the key criteria. This process includes computing Cronbach’s alpha ($\alpha$), computing Coefficient of Variation (CoV), prioritization using Fuzzy TOPSIS, computing Kendall’s Coefficient of Concordance (KCC) and Pareto analysis. The $\alpha$ value greater than 0.7 indicates that the response values obtained are valid and reliable. The CoV is also utilized as another method to check the consistency. CoV value of 0.30 is considered as not too high for qualitative assessments. Further, the response matrix is analyzed using Fuzzy TOPSIS [36]. Additionally, applying the Pareto rule, the criteria which form the top 80% of the weight is filtered in,
and the rest of the 20% criteria are marked for elimination. Also, the level of agreement between expert perception is tested using KCC. At a 5% significant level, a p-value <0.05 denotes the degree of agreement between experts is significant.

2.4. Scalability of the adopted methodology
This study proposes a framework to arrive at the critical sustainability criteria with the help of MCDM methods. The adopted method could be replicated in other regions by reviewing local standards and also by involving experts from the particular region of interest. Thus, the proposed method and results can be replicated in different contexts and for different occupancies.

3. Identification of criteria
An initial pool of 101 criteria is identified and classified under eleven categories and three sustainability dimensions. The six categories which fall under the environmental dimension include Sustainable sites (17 criteria), Energy efficiency (14 criteria), Water efficiency (10 criteria), Pollution reduction (5 criteria), Material conservation (9 criteria) and Waste management (4 criteria). Four categories fall under the social dimension include Environmental quality and well-being (19 criteria), Usability and functionality aspects (13 criteria), Integrative process and documentation (3 criteria) and Safety and security (3 criteria). The single category which falls under the economical dimension is the Cost and economic aspects (4 criteria).

Sustainable sites category helps to reduce automobile use, fossil fuels, emissions and encourages the use of alternatives to accomplish the SDGs such as ‘Responsible consumption and production’, ‘Affordable and clean energy’, ‘Sustainable cities and communities’ and ‘Good health and well-being’. The Energy efficiency category encourages reduced energy consumption and the use of renewable and clean energy to accomplish the SDGs such as ‘Responsible consumption and production’, ‘Sustainable cities and communities’ and ‘Affordable and clean energy’. Water efficiency category encourages the use of water in a self-sustainable manner by reducing, recycling and reusing strategies, thereby accomplishing the SDGs ‘Clean water and sanitation’, ‘Sustainable cities and communities’ and ‘Responsible consumption and production’ with specific focus to water use. Pollution reduction category covers multiple SDGs, including ‘Good health and well-being’, ‘Clean water and sanitation’ and ‘Life on land’ and aims to reduce the impact on surrounding communities and environments arising from material production, building occupation/operation. The Material conservation category encourages the use of recycled/reused material and discourages the use of non-renewable resources and covers SDGs such as ‘Responsible consumption and production’, ‘Good health and well-being’, ‘Sustainable cities and communities’, and ‘Life on land’. Waste management category ensures proper segregation and management of waste and helps to accomplish the SDGs ‘Sustainable cities and communities’ and ‘Life on land’. Environmental quality and well-being category has a direct influence on the health and well-being of occupants and helps to accomplish the SDGs ‘Sustainable cities and communities’ and ‘Good health and well-being’ by addressing various aspects like minimum daylighting, thermal comfort, acoustic comfort, visual comfort and proper ventilation. The Usability and functionality category encourages the adoption of sustainable design measures like space optimization, passive design strategies, universal design, flexibility, adaptability and is closely linked with the SDG ‘Responsible construction and production’. The Integrative process and documentation category encourage the adoption of sustainable management practices like stakeholder consultation, preparation of project brief and green guidelines and try to establish the SDG ‘Quality education’. The objective of the Safety and security category is to devise a design concept that prevents risks/hazards in buildings and their immediate vicinity as much as possible and is closely linked with multiple SDG’s including ‘Industry innovation and infrastructure’ and ‘Sustainable cities and communities’. The objective of Cost and economic aspects category is to assess the cost incurred throughout the life cycle of a building, thereby encouraging sensible and informed decision on the use of economic resources and helps to accomplish the SDGs ‘No poverty’, ‘Sustainable cities and communities’ and ‘Responsible consumption and production’. 
4. Results and Discussion

4.1. Reliability and Consistency of collected data

The expert responses recorded in the form of a data matrix is checked for reliability and consistency. The α value for all the eleven categories is calculated and found to be above 0.7, indicating consistent and reliable response values. Pollution reduction, Material conservation, Waste management and Cost and economic aspects categories showed a CoV value less than 0.30. The rest of the categories showed a CoV value between 0.3 and 0.4, indicating a lack of consensus among experts.

4.2. Arriving at the critical criteria

The degree of importance of each criterion under all the eleven categories are computed using Fuzzy TOPSIS and the results are presented in the form of Pareto charts. Also, the KCC and the p-value were computed in SPSS. The KCC value indicates that there is a moderate agreement between the expert judgements for categories Energy efficiency, Pollution reduction, Usability and functionality aspects and Cost and economic aspects. The corresponding p-value for all the four categories shows that the degree of agreement is significant. The KCC value for the rest of the seven categories indicates that there is a weak agreement between the expert judgements. However, the corresponding p-value suggests that the degree of agreement between the experts is insignificant. Since the survey was conducted among experts from different domains, it is unlikely to reach consensus. Finally, arrived at the list of key criteria and presented in Table 1.

Figure 1 shows Pareto chart for the Sustainable sites category. Four criteria cover the bottom 20% weight in the Sustainable sites category which includes ‘Home office’, ‘Electric charging facility for vehicles’, ‘Bicycle storage’, and ‘Accessibility/in proximity to basic house-hold amenities’. The practice of working from home is not so frequent in India, therefore achieved a lower weight for the ‘Home office’ criterion. The implementation of electric vehicle technology in India is in its early stage, and it might be the possible reason for the lower weight of the criterion ‘Electric charging facility for vehicles’. The infrastructure facilities currently existing in the country are not sufficient to support a safe bicycle drive, which may have prompted the experts to give lower weight for the ‘Bicycle storage’ criterion. Another criterion that showed lower weight is ‘Accessibility/in proximity to basic house-hold amenities.’ Thus 13 criteria were included in the key criteria list from the Sustainable sites category.

Similarly, all the categories were analyzed using Pareto charts. The criteria which cover the bottom 20% weight in the Energy efficiency category include ‘Embodied energy in materials for maintenance and replacement’, ‘Efficient hot water distribution system’, ‘Water heating system’, and ‘On-site renewable energy’. The overall quantity of maintenance and replacement materials is considerably less in case of a building lifecycle that may have prompted the respondents to provide low weight to criterion ‘Embodied energy in materials for maintenance and replacement’. The lower weight for hot water-related criteria might be due to the meagre requirement of hot water systems in tropical climates. The
On-site renewable energy also got lower weight since in most of the projects, the solar panels installed with batteries prove to be economically infeasible. Thus, ten criteria were included in the critical criteria list from the Energy efficiency category. ‘Leak detection’ criteria and ‘Leak isolation’ criteria cover the bottom 20% weight in the Water efficiency category. A possible explanation for these results might be the lack of awareness among stakeholders, or else the respondents have perceived higher importance to other criteria among the category. Thus, eight criteria were included in the critical criteria list from the Water efficiency category. The ‘Light pollution’ criteria itself covers the bottom 20% weight in the Pollution reduction category. The ‘Light pollution’ criterion might not directly create a negative impact on the comfort of the occupants, and the low weight obtained for this criterion is possibly reflecting this concept. Thus, four criteria were included in the critical criteria list from the Pollution reduction category. ‘Reuse of salvaged materials’ and ‘Ease of disassembly, reuse or recycling of construction materials’ criteria cover the bottom 20% weight in the Material conservation category. Even though the reuse of salvaged materials in construction adds to the sustainability of a building, the criterion obtained low weight. This result might be due to a lack of awareness. The concept of decommissioning of a building is not practiced in the Indian context; instead, more importance is given to adaptive reuse and might be the possible reason for low weight obtained for the ‘Ease of disassembly, reuse, or recycling of construction materials’ criterion. Thus, seven criteria were included in the critical criteria list from the Material conservation category. Since the Waste management category is limited to four criteria, ‘Use of compost/sludge/waste for organic farming’ criterion itself covers the bottom 20% weight. The respondents may have perceived higher importance to other criteria among the category. Thus, three criteria were included in the critical criteria list from the Waste management category.

The criteria which cover the bottom 20% weight in the Environmental quality and well-being category include ‘Private space’, ‘Tobacco smoke control’, ‘External lighting’, ‘Visual privacy’ and ‘Glare Control’. All these criteria received a low weight comparing its relative importance to other criteria present in the category. Thus 14 criteria were included in the critical criteria list from the Environmental quality and well-being category. The criteria which cover the bottom 20% weight in the Usability and functionality category include ‘Climate-sensitive design’, ‘Parking facilities for visitors’, ‘Accessible design for all’, and ‘Denying daylight of adjacent property’. ‘Climate-sensitive design’ and ‘Accessible design for all’ is an important criterion; however, received a low weight and it is difficult to explain this result. In the case of homestead developments providing parking space for the visitor may not be a viable solution with a limited amount of land available for construction. This may have prompted the respondents to give a low weight to the criterion. ‘Denying daylight of adjacent property’ prompts the responsibility towards the adjacent property; however, received a low weight comparing its relative importance to other criteria present in the category. Thus, nine criteria were included in the critical criteria list from the Usability and functionality category. The Integrative process and documentation category are limited to three criteria and a single criterion ‘Comprehensive project brief’ itself covers the bottom 20% weight. Thus, two criteria were included in the critical criteria list from the Integrative process and documentation category. Since the Safety and security category is limited to three criteria, the ‘Security’ criterion itself covers the bottom 20% weight. The security aspects are incorporated in a building even after the building construction. However, the other criteria in the category should be carefully dealt with during the design stage. This aspect might have resulted in low weight for ‘Security’ criterion. Thus, two criteria were included in the critical criteria list from Safety and security category. ‘Preconstruction cost’ criterion covers the bottom 20% weight in the Cost and economic aspects category. The preconstruction cost includes only a very minimal percentage of the total cost of the building, and this might be the possible reason for the low weight. Thus, three criteria were included in the critical criteria list from Cost and economic aspects.

| Table 1. List of key criteria |

| Environmental dimension |
|--------------------------|
| Sustainable sites category: 1. Previously occupied land/Brownfield development; 2. Access to public services; 3. Proximity to public transport; 4. Ease of access to open space and recreational area; 5. Use of topsoil for landscape; 6. Control soil erosion; 7. Avoid disturbance to natural topography or vegetation; 8. Enhancing site ecology; 9. Vegetation for ambient outdoor cooling; 10. No invasive plants and use of local plants; 11. Stormwater management; 12. Heat island effect, non-roof; 13. Heat island effect, roof; |
Energy efficiency category: 1. Embodied energy in construction materials; 2. Energy performance; 3. Renewable energy power back up; 4. Efficient HVAC distribution systems; 5. Energy efficient equipment; 6. Energy metering; 7. Efficient lighting system; 8. Thermal efficiency of building envelope; 9. Good fenestration design; 10. Air infiltration;
Pollution reduction category: 1. CFC-free equipment; 2. Carbon emissions; 3. Water pollution; 4. Noise pollution;
Material conservation category: 1. Materials with recycled content; 2. Local and traditional materials; 3. Rapidly renewable building materials and certified wood; 4. Use of virgin non-renewable materials; 5. Alternative construction materials and technologies; 6. Re-use of existing structure; 7. Designing for durability and resilience;
Waste management category: 1. Separation of house-hold waste; 2. Organic waste management, post occupancy; 3. Inorganic waste management post occupancy;

Social dimension
Environmental quality and well-being category: 1. Daylighting; 2. Internal lighting; 3. Zoning and occupant control for lighting; 4. Fresh air & cross ventilation; 5. Exhaust systems; 6. Low VOC materials, paints & adhesives; 7. Avoid hazardous materials; 8. Air filtering and contaminant control; 9. Indoor air quality (IAQ) plan; 10. Thermal comfort; 11. Thermal zoning and controls; 12. Acoustic comfort and sound insulation; 13. Access to exterior views from interior; 14. Community spaces;
Usability and functionality aspects: 1. Optimal use of resources; 2. Organic farming; 3. Facilities for service staff; 4. Spatial efficiency; 5. Volumetric efficiency; 6. Flexible floor plan; 7. Flexible building structure; 8. Ability to modify facility technical systems; 9. Adequacy of building envelope for maintenance;
Integrative process and documentation category: 1. Stakeholder consultation; 2. Green home guidelines/strategy;
Safety and security category: 1. Firefighting and fire detection system; 2. Measures for seismic safety;

Economic dimension
Cost and economic aspects: 1. Construction cost/building cost; 2. O and M cost; 3. Residual value;

5. Conclusion

There were many efforts in the built environment for establishing the sustainability criteria, well acknowledged in the form of building rating systems and sustainability assessment systems. However, these systems rarely explore the dimensions of sustainability holistically and motivated researchers to explore the study area and establish the key sustainability criteria for various contexts. This article established the critical criteria influencing the sustainability of residential buildings in the tropical climate of India. The study adopted questionnaire survey to record the opinion of building industry experts on sustainability criteria. Fuzzy TOPSIS method was used to arrive at the degree of importance of each criterion by analyzing the collected data. Additionally, Pareto analysis was conducted to extract the most important criteria and eliminate the less important ones. The results of Fuzzy TOPSIS were also tested to find the agreement between the expert opinion using KCC.

Multiple SDGs are being addressed with the help of the established criteria under eleven categories. SDG 1 is being addressed in Cost and economic aspects by monitoring the cost and value aspects, thereby reinforcing the importance of affordable housing. SDG 3 is addressed in several categories including Sustainable sites, Pollution reduction, Material conservation, Environmental quality and well-being. SDG 4 is addressed in the Integrative process and documentation category which tries to create an awareness in sustainable development in the built environment. SDG 6 is taken care of by the Water efficiency and Pollution reduction category. SDG 7 is addressed in Energy efficiency and Sustainable sites category. SDG 9 is addressed in the Safety and security category by urging for resilient infrastructure. SDG 11 is taken care of by several categories, including Sustainable sites, Energy efficiency, Water efficiency, Material conservation, Waste management, Environmental quality and well-being, Safety and security, Cost and economic aspects. SDG 12 is also addressed in several categories such as Sustainable sites, Energy efficiency, Water efficiency, Material conservation, Usability and functionality aspects, Cost and economic aspects. SDG 15 is addressed by categories such as Pollution reduction, material conservation and waste management. These set of critical criteria closely linked to multiple SDGs could be utilized to develop a sustainability assessment system based on further studies. In conclusion, this research proposes a methodological framework to establish the critical criteria in case of multi-criteria decision-making problems especially in the area of sustainable development. The adopted approach and the results can be replicated in a variety of contexts for further studies to consider sustainable development holistically.
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