Journal of Building Engineering 35 (2021) 102003

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

An analytical hierarchy based optimization framework to aid sustainable assessment of buildings

Amarnath Payyanapotta, Albert Thomas *

Civil Engineering Department, Indian Institute of Technology Bombay, Mumbai, India

ARTICLE INFO

Keywords:
Sustainable building design
LEED
ECBC
Analytical hierarchy process

ABSTRACT

Buildings are a significant consumer of energy and resources, thereby urging the designers, architects, and policymakers to place a great deal of effort in achieving and implementing sustainable building design strategies. Energy conservation codes and green building rating systems help a great deal in this by measuring the effectiveness of these strategies and thereby enhancing overall building sector performance in social, environmental, and economic perspective. However, for a developing country such as India, the steadily growing population and the rapid rate of urbanisation impose a burden on the country's limited and continuously decreasing resource base, including the land available for construction. The number of sustainable rated or buildings compliant to energy standards is minimal in India, primarily due to the complexity and obstinate nature of the assessment systems/regulations that restrict the stakeholders and designers in proper implementation and utilisation of these rating systems. This study, therefore, aims to introduce a data-driven and user-friendly framework that cross compares the green building rating systems and energy conservation codes predominant in India. Subsequently, it helps the users to evaluate their proposed building design based on various sustainability-driven preferences. This framework utilises the information collected from the user to generate code-compliant building design strategies by employing the Analytical Hierarchy Process that considers the building's current sustainability level and incorporating the user's preferences in improving the overall sustainability of the buildings. The proposed framework has prospects to encourage users to test the efficiency of various sustainable construction practices and promote more sustainable buildings in the country.

1. Introduction

The building industry consumes a significant share of natural resources for its construction and operation. Globally, it accounts for about 40% of resource use, 44% of the total energy consumption, and about 16% of world's annual use of water [1–3]. Indian condition is nowhere different, where the buildings account for 33% of the final energy consumption [4,5]. Moreover, with around 17.5% of the 'world's population, and a rapidly growing urban community, the country is cautioned to end up in various environmental issues in the next few decades [6]. Evaluating and measuring the sustainability aspects of buildings thus becomes essential.

According to the U.S. Green Building Council [36], construction and use of green buildings result in energy savings of 30%, carbon emission savings of 35%, and savings in water use of 30–50%. Towards measuring the sustainability level of a building, several rating systems and standards are also introduced in the past few decades across the globe, with LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) being the most adapted ones globally [36]. LEED-India and GRIHA (Green Rating for Integrated Habitat Assessment) are the prominent ones in the Indian scenario [7]. LEED-India is proposed by Indian Green Building Council (IGBC), while GRIHA is proposed by Energy and Resources Institute in 2007. LEED-India promotes a holistic methodology of sustainability assessment by understanding the functioning and properties of the building. The content and structure of the assessment system are based on the internationally prominent LEED program by U. S. Green Building Council (USGBC), with necessary alterations based on the Indian construction needs. Meanwhile, GRIHA is developed exclusively to suit Indian requirements.

In addition to the rating systems mentioned above, mandatory regulations and environmental standards by government or non-governmental organisations were also a significant factor in developing a sustainable construction culture [8]. The regulatory code that

* Corresponding author.
E-mail addresses: amarnathpayyanapotta@gmail.com (A. Payyanapotta), albert@iitb.ac.in (A. Thomas).

https://doi.org/10.1016/j.jobe.2020.102003
Received 2 January 2020; Received in revised form 17 October 2020; Accepted 8 November 2020
Available online 13 November 2020
2352-7102/© 2020 Elsevier Ltd. All rights reserved.

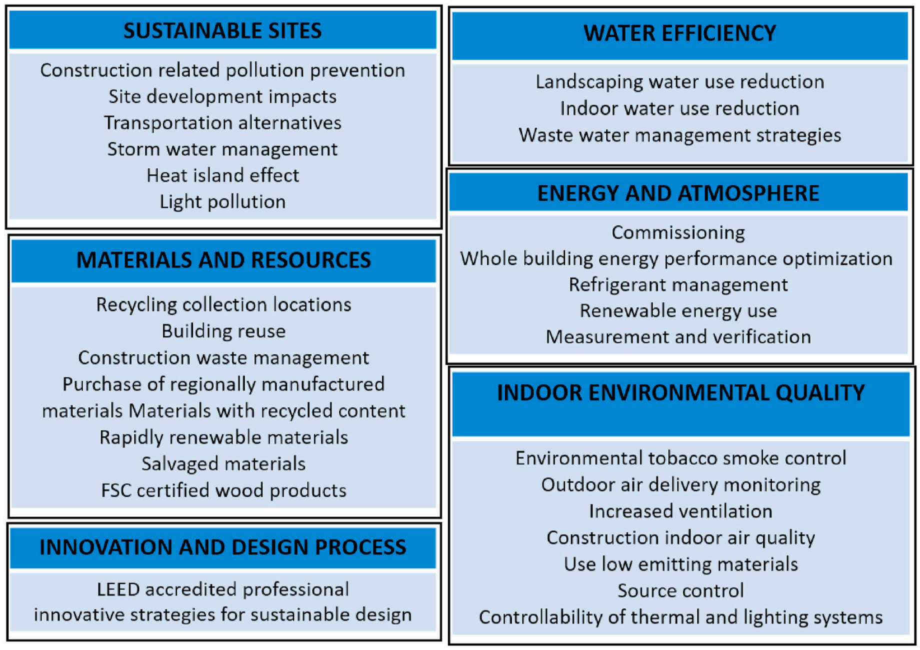


Fig. 1. Summary of LEED-India categories.

currently establishes the minimum energy performance standards for Indian commercial buildings is the Energy Conservation Building Code (ECBC) launched by the Bureau of Energy Efficiency in 2007. An ECBC compliant building is reported to save a minimum of 25% of energy, and rigorous implementation of ECBC is expected to result around a 50% reduction in overall energy consumption by 2030 [15]. Consequently, these regulatory systems and the rating systems discussed earlier assess the sustainability of buildings and help to improve the quality of life of people in social, economic, and environmental dimensions.

However, even though the rating systems and standards are available for use, the number of ECBC compliant and green rated buildings in India is still negligible [9]. Despite the urgent requirement and awareness of greener practices in the construction industry, clients and developers remain unsuccessful in implementing green procurements in local construction industries [8]. There are several reasons for this. The present sustainable rating systems are complicated, making it difficult for the building users, clients, and designers to work with [10]. Similarly, the obstinate nature of rating systems, lack of awareness among users, and lack of skilled professionals have also made the process of achieving required performance ratings tiresome [11–13]; and [9]. This has resulted in less penetration of these rating systems and the frameworks among the building community. Therefore, the main objective of this study is to develop a framework that eases the process of sustainability assessment of buildings and incorporates the various stakeholder's sustainability-related preferences also into the assessment process.

2. Background and motivation

The vision of the IGBC through LEED-India is to provide a sustainable built environment for everyone. Credits are awarded to projects based on their performance related to several fields such as sustainable site development, water efficiency, energy efficiency, material and resources selection, and indoor environmental quality. The detailed attributes considered for sustainability assessment under each of these six categories are shown in Fig. 1 below. Upon reviewing these attributes, LEED-India awards certification to a building along with four different levels, which are Certified, Silver, Gold, and Platinum.

Similarly, in 2007, The Energy and Resources Institute, India, also developed a green building rating system named as Green Rating for Integrated Habitat Assessment [14]. GRIHA assesses the sustainability performance of buildings and rates the building from single to five-star standards. Different categories, under which LEED and GRIHA are grounded upon are summarised in Table 1 below. Both the rating systems showed a trend of giving energy efficiency the highest priority, followed by materials and resources and then the sustainable site choices and water efficiencies. Further, different parameters are considered for scoring in other assessment methods. E.g., LEED included a score for pedestrian and cyclist safety. At the same time, the GRIHA rating system does not have such consideration. However, Vyas and Jha [10] raised the concern that some more aspects contribute to the overall sustainability, such as geographic factors and loss of habitat, which are not accounted for in the current rating systems. Therefore, even though the rating systems seem comprehensive enough, there is still a scope of modification considering some of the above criteria, and similarly many others.

Table 1
Major categories under which the buildings are rated in LEED, GRIHA (Adapted and modified from Ref. [7]].

LEED	
ENVIRONMENTAL CATEGORY	Weighted %
SUSTAINABLE SITES	23.1%
WATER EFFICIENCY	9.1%
ENERGY & ATMOSPHERE	31.9%
MATERIAL & RESOURCES	12.7%
INDOOR ENVIRONMENTAL QUALITY	13.6%
REGIONAL PRIORITY	3.6%
INNOVATION	6%
TOTAL	100%
GRIHA	
ENVIRONMENTAL CATEGORY	Weighted %
SITE SELECTION & SITE PLANNING	23.1%
CONSERVATION & EFFICIENCY OF RESOURCES	9.1%
BUILDING OPERATION & MAINTENANCE	31.9%
INNOVATION	6%
TOTAL	100%

Other regulatory systems that enforce sustainable construction are the various codes and standards. Building energy regulations, such as standards and codes, exist in almost all developed and developing countries. The main objective of these regulations is not only conservation of energy but also to ensure the health and safety of building occupants. While rating systems generally help to assess the sustainability level in buildings, the ways of ensuring sustainability before a design is through the implementation of various energy codes and standards. Energy codes and standards set minimum performance requirements for buildings to realise a reduction in energy use and emissions over the entire lifecycle of the building. International Energy Conservation Code (IECC) is one such standard implemented by the International Code Council (ICC) in 1998 [36]. Similarly, the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) in 1975, presented the requirements for the buildings to meet to become energy efficient, through an energy standard ASHRAE 90.

In an Indian scenario, the primary code is the Energy Conservation Building Code (ECBC), which is developed by the Ministry of Power and Bureau of Energy Efficiency (BEE) in 2007 [15]. It is developed based on ASHRAE standards and has two paths: Prescriptive and whole building performance methods for demonstrating code compliance. Buildings applying for ECBC compliance shall comply with all mandatory requirements, irrespective of the compliance path. For compliance through the prescriptive approach, the buildings should meet the prescribed values in all criteria provided by ECBC and the agreement with the mandatory requirements. Moreover, compliance through the whole building method is provided if the estimated annual energy use for the proposed building design is less than that of the standard design provided by ECBC. The objective of ECBC is to provide minimum energy standards for commercial buildings with a connected load of 100 kW. The latest version of ECBC is launched on June 19, 2017, which includes actions of energy conservation through optimising various building design elements [15]. ECBC prescribes techniques and parameters for an energy-efficient building in mainly three categories: ECBC compliant, ECBC plus, and Super ECBC. Energy Conservation Building Code (ECBC) is a robust regulation to encourage the transition of buildings to efficient use of energy. It is one of the first building codes in the country to set provisions for achieving energy neutrality in buildings. Due to consistent efforts by the Bureau of Energy Efficiency (BEE) and other bilateral projects, awareness about promoting energy efficiency in buildings and ECBC got onto the agenda of different state governments in the country.

India ranks third among the top ten countries with the maximum number of green-rated buildings in the world [36]. However, the number of buildings that are green-rated is less than 5% of the total number of buildings in the country [16]. In addition, when compared against the population and land area available in the country, sustainable buildings in India are far below compared to countries like the USA and UK. Overall, the LEED-India system is the most preferred method of green certification generally by private sector companies in India [6], and ECBC has not received much attention so far. This is mainly because of the implementation of green building assessment technologies and standards that encounter several kinds of barriers and problems [9].

There are several reasons for this shortfall of green rated buildings in the country. The primary role of every green building rating system or any regulatory tool is to curb the environmental impacts. Therefore, these systems must consider a broader range of environmental criteria, making these assessment methods too comprehensive [16]. For instance, green building assessment systems such as LEED-India, GRIHA, and Eco-housing Assessment tool uses 51, 34, and 74 sustainable criteria, respectively to assess the building [10]. Similarly, Ali et al. [12] discussed that measuring green buildings in developing countries such as Jordan uses 41 indicators of sustainability. Similarly, Alyami, Rezgui, and Kwan [17] estimated the greenness of residential buildings in Saudi Arabia by compiling 92 criteria from various international green rating systems. Consequently, the environmental building assessment method always tends to be comprehensive by incorporating all the environmental measures as well as economic and social aspects. This exhaustive approach has made these tools a much complex system that requires large quantities of data and the requirement of skilled professionals for analysis.

On a similar note, regulatory standards such as ASHRAE 90.1 works on the single dimension of energy conservation, and they estimate the performance of the building only on the simulated energy consumption [18]. Many studies suggested that such a single-dimensional assessment technique cannot be regarded as the best approach [19]; and [20]. Janikowski et al. [21] argued that it is inappropriate to assess buildings using one criterion or attribute. They advocated the need to accept a multi-dimensional perspective that contains the spectrum of characteristics regarding sustainable development.

Similarly, each building assessment system is designed against preset environmental criteria and are likely to be considered only at the end of the design stage of the project to evaluate and rate the performance of the building. However, Ding et al. [11] argued that instead of only relying on the design stage to achieve sustainability or to minimise impacts of buildings, it is advisable to use the tools more at a conceptual stage. Likewise, studies by Crawley and Aho [22] and Cole [23] emphasised that an effective way of ensuring sustainability is to incorporate environmental assessments in the conceptual and pre-design stage. Similarly, according to Crookes et al. [24]; such assessments act as a more efficient tool during the identification and preparation stages of the construction project. Ding et al. [11] also stated that “Striking a balance between completeness in the coverage and simplicity of use is one of the challenges in developing an effective and efficient environmental assessment tool."

Further, the concept of sustainability has now widened to the triple bottom line concept, which refers to the social, environmental and economic performance of the building, which is inter-related to the goals of sustainable development [3]. Furthermore, the term building performance and sustainability definition vary according to the varying interests of parties involved in the building development [10]. For instance, the owner or the contractor of the building will be giving more priority to cost and energy efficiency. At the same time, the occupants also look at comfort, indoor air quality, and health of the building, in addition to the cost aspects. Thus, along with achieving the required rating and code compliance, it is equally important to consider the user requirements for adopting changes to achieve the required level of performance.

In summary, several aspects necessitate the need for this study, such as the complexity in the existing rating systems, prospects of employing these systems and techniques as design guidelines for sustainable buildings, and other shortcomings of adopting a single assessment approach for incorporating the ’user’s preferences. Therefore, there is a need for a framework that adopts a multi-criterion assessment framework that includes user’s needs and puts forward a way to utilise these systems as a design tool that provides better suggestions to improve the performance of the user’s building. Such a framework could be used as a design tool for improving the performance of the building and thereby completes the balance between the abundance and simplicity of these assessment systems. Therefore, the main objectives of this study are.

1. Develop a database and an interface summarising the major green building rating systems and the regulatory standards in India by evaluating the various criteria involved in the sustainability assessment.
2. Utilise the above interface and develop a framework that can readily evaluate the sustainability scores of a proposed building and provide suggestions to improve their respective scores also based on the ’user’s preferences.
3. Perform a case study by incorporating ’user’s preferences to demonstrate the usability of the proposed framework.

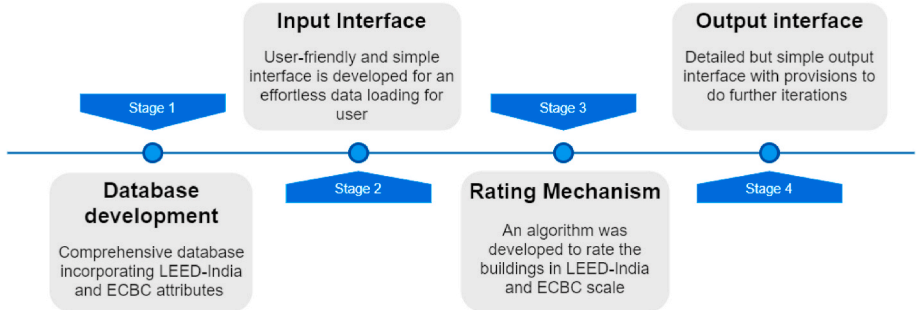


Fig. 2. Research methodology- phase 1.

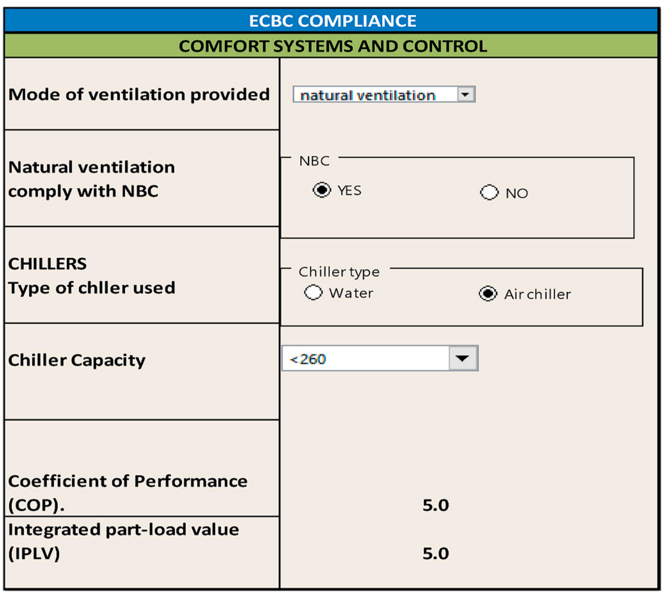


Fig. 3 (a). Snapshot of input interface for ECBC Compliance.

3. Research methodology

To achieve the objectives mentioned above, the methodology adopted consists of two phases. The first phase develops a comprehensive database-driven tool that allows a user to identify the rating and compliance level of a given building, based on the existing building design parameters. It will enable the user to understand where the building currently stands. This tool is designed to make it non-restrictive to professionals and to give the freedom to analyse among various techniques to be incorporated in the building and its corresponding effects on the overall sustainability-based score. In the second phase, the tool is modified with an add-on that provides the users with an option to input the desired rating/compliance level and sustainability-based priorities. These preferences are analysed through an analytical hierarchy process to generate design specific suggestions to achieve the desired levels. Overall, the framework developed through these two phases is designed to help a user to simplify the regulatory framework and gather quick reflections on achieving the desired sustainability level.

3.1. *Framework: phase 1*

A block diagram representing different stages of the research methodology for Phase-1 of this study is shown in Fig. 2 below. As can be seen from the figure, phase- 1 has four stages. In Stage 1, a comprehensive database is developed, incorporating all criteria, sub-criteria, and

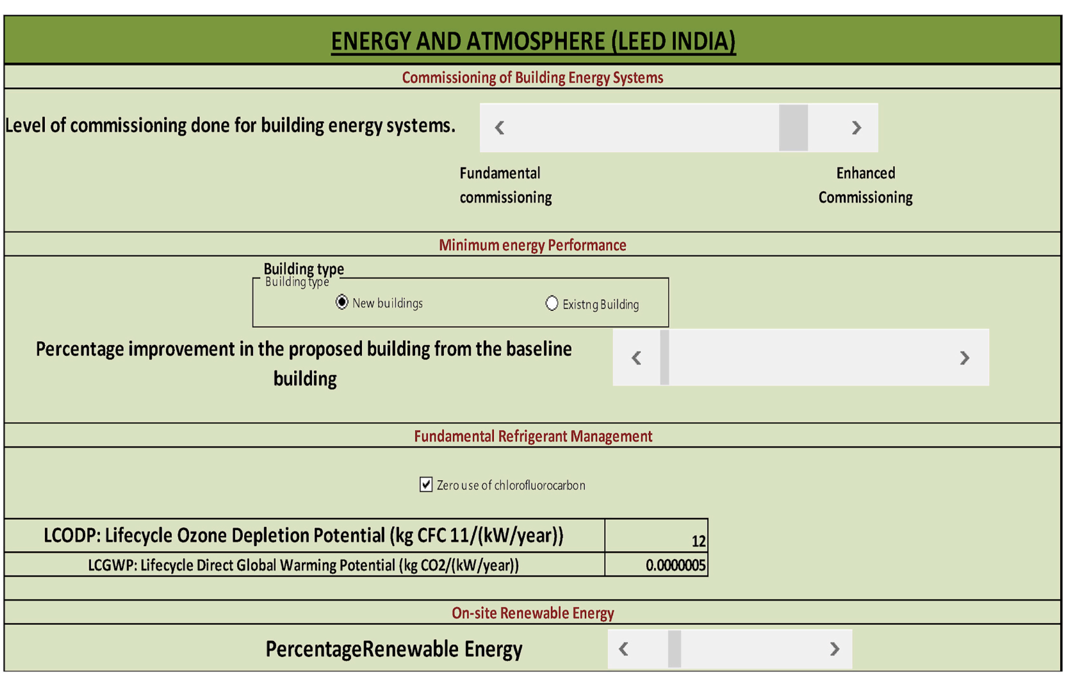
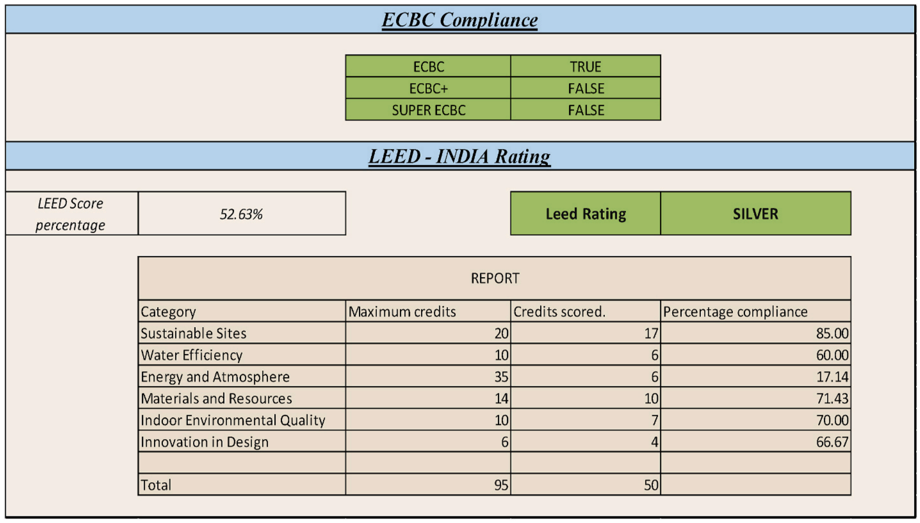


Fig. 3 (b). Snapshot of input interface for LEED-India attributes.



ECBC Compliance

ECBC	TRUE
ECBC+	FALSE
SUPER ECBC	FALSE

LEED - INDIA Rating

LEED Score percentage	52.63%	Leed Rating	SILVER

REPORT

Category	Maximum credits	Credits scored.	Percentage compliance
Sustainable Sites	20	17	85.00
Water Efficiency	10	6	60.00
Energy and Atmosphere	35	6	17.14
Materials and Resources	14	10	71.43
Indoor Environmental Quality	10	7	70.00
Innovation in Design	6	4	66.67
Total	95	50	

Fig. 4. A snapshot from the output interface.

alternatives considered in LEED-India and ECBC. This database is developed in Microsoft Excel 2016, detailing all attributes and the credits a building can secure based on the different techniques. The database has several sections to measure the building specifics and grant credits in ECBC, ECBC+, and the SuperECBC scale, which are the different levels of ECBC compliance [15]. The database is divided into sustainable sites, water efficiency, energy efficiency, indoor air quality, and material and resources such as in LEED-India.

In Stage 2 of phase-1, an input interface is developed that allows the user to input general details about the building, such as the techniques adopted and the building material properties used for the construction. The interface also includes data inputs required for all the five major categories of LEED-India and the attributes needed for ECBC compliance. The information needed for assessing the ECBC compliance is achieved through four major classifications, namely HVAC, building envelope, control systems, and electrical systems related inputs. Form controls, ActiveX controls, VBA, and macros in Microsoft Excel are used to ensure the interface is handy and allows the user to provide data effortlessly. A snapshot from the interface for ECBC compliance inputs (comfort systems and controls) is shown below as Fig. 3(a), and for LEED-India attributes (energy and atmosphere) is shown in Fig. 3(b). For making the input interface user friendly and equally understandable to non-professionals, the default inputs were provided against each input option for typical buildings that are constructed in the country. However, the users can choose any options as per the building they would like to assess the sustainability levels. Subsequently, through Stage 3, an algorithm is developed that compares user's data about the building with the database developed in Stage 1 to evaluate the building's ratings and the compliance level against ECBC and LEED-India.

Similarly, as a final step, an output interface is designed through Stage 4 to communicate the results. Through this output screen, relative rating levels in LEED-India such as Certified, Silver, Gold, or Platinum and the compliance level in ECBC such as ECBC, ECBC+, or SuperECBC, which the assessed building can achieve as per entered details are displayed. Along with this, the user output interface also delivers a detailed report on the credits gained by the project based on the performance related to the five different categories in the database, and thereby help the user to clearly understand the discrepancies in the proposed project. This also helps the user to recognise the criteria or property of the building that falls behind in the scale of sustainability and plan methods to improve those attributes. A snapshot of the output interface from the developed framework is shown in Fig. 4 below.

3.2. Framework: phase 2

While Phase 1 is aimed at predicting the sustainability ratings based on the user entered inputs, Phase 2 is designed for helping the users to design their specific building based on their preferences on desired

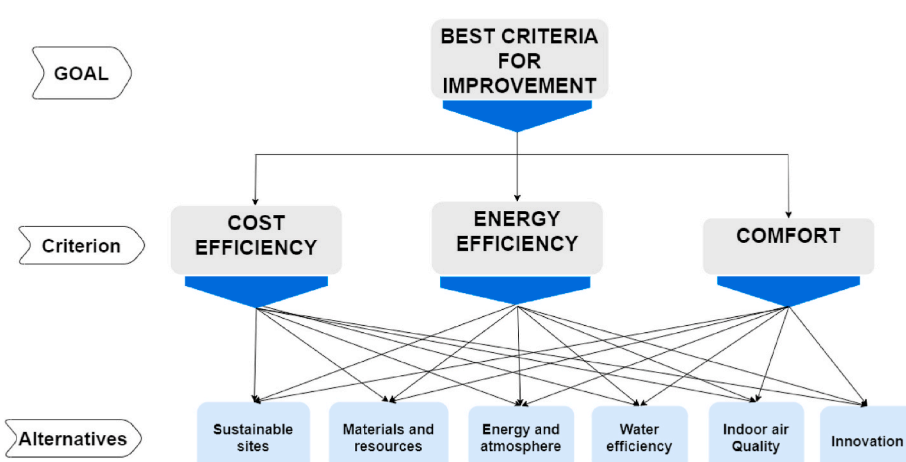


Fig. 5. AHP hierarchy model.

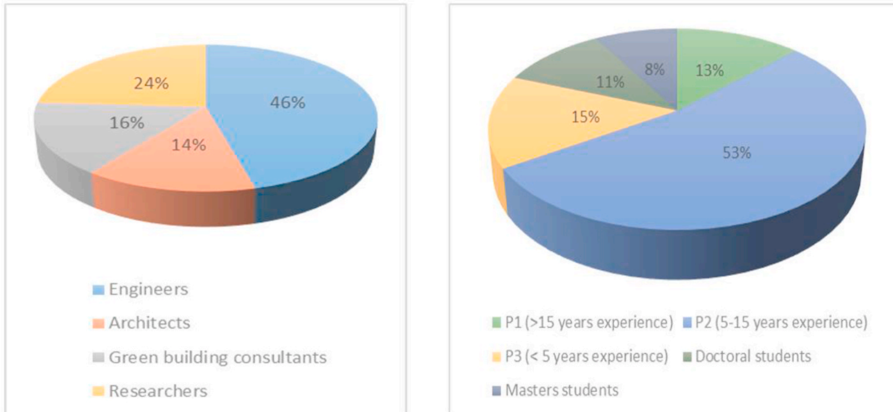


Fig. 6. Distribution of respondents on their experience and professional affiliation.

ratings (e.g., a platinum level in LEED against a current silver rating), subjected to three design parameters such as cost efficiency, energy efficiency, and comfort level. These preferences are collected from the users and are analysed using Analytical Hierarchy Process [25]. The Analytical Hierarchy Process is a multi-criteria decision-making tool developed by Thomas Saaty. AHP prioritises various desired alternatives by quantifying them on a ratio scale based on the judgment of the decision-maker. Weights for each alternative are calculated based on pairwise comparison of inputs, by finding the dominant right eigenvector of a positive reciprocal decision matrix [26]. The major strength of this approach is that it provides a structured but simple solution to the decision-making problem by considering both tangible and intangible components in a structured manner [27].

The primary purpose of AHP involvement in this study is to optimise and provide the best suggestions for the user to improve the overall sustainability levels of a proposed building, form the identified level in Phase-1. Generally, decision-making through AHP involves few steps, namely hierarchical structuring of the goal or the problem, data collection, finding local and global weights, checking the consistency of judgements, and finally finding a solution to the problem [28,29]. The hierarchical structure developed for formulating the AHP model in this study has three levels, as shown in Fig. 5 below. The topmost level describes the decision problem or goal. The developed model aims at finding the best suitable criteria when improved will guide the building to perform as per the user requirements and achieve the required level of sustainability rating. The second level corresponds to gathering the attributes that the user needs modifications in the building, such as cost efficiency in construction and operation, energy efficiency in building operation, and comfort of the building occupants, in their corresponding weights. The lowest level corresponds to the alternatives which the AHP model is designed to prioritise. These alternatives are the criteria considered for ratings in LEED-India such as sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor air quality.

The model proposed through Fig. 5 prioritise the various alternatives based on their weights calculated upon compiling local and global weightages from the AHP hierarchy. Local weightages are those attained by cross comparing each pair of alternatives concerning the categories. Global weights are those developed by comparing each pair of categories concerning the goal of the analysis. In the developed framework, the local weightages are determined using the AHP technique, while the global weightage is what the users have provided as their priority on the criterion. Consequently, these weights benefit from finding the priority order for implementing suggestions to different criteria to achieve the required rating and user desideratum. The consistency of judgements is analysed relative to the large samples of randomised judgements by calculating the consistency Ratio (CR). If the CR is estimated to be much higher than 0.1, the judgements are considered to be inconsistent or not trustworthy as they are closer to randomness and needs to be repeated [30].

3.3. AHP data collection

To develop a robust and precise result from the AHP analysis, the process of local weight determination is carried out through an online survey by contacting a group of investigative experts. Global weights for this analysis are the priorities provided by the user as their requirement for the building (Three criteria in Fig. 5). A web-based AHP online system (AHP-OS) developed by Goepel, K.D. [26]; is adopted with necessary modifications for this survey. This platform is adopted because it provided unique features such as a user-friendly interface, handling group inputs, calculation of group consensus, and support to improve inconsistent responses. The survey is conducted among experts that included civil engineering professionals, LEED experts, architects, doctoral and postgraduate researchers working in the building sustainability domain.

The selection of experts for the survey and their representativeness of the total population is taken care of with at most importance in this study. The significant factors considered were the respondent's profession, experience in sustainability, educational and other qualifications in the field of green buildings. The user group represented in the survey and their corresponding level of experience is shown in Fig. 6 below. P1 represents the professionals having more than 15 years of experience in their respective fields, while P2 and P3 represent professionals with years of experience between 5 and 15 and less than five years, respectively. These group of professionals included engineers, architects, and green building consultants. The reason for including green building consultants among the respondents is their awareness about green buildings and the better knowledge they hold regarding the intricacy of the current rating systems. The respondents also included doctoral and graduate researchers who are doing their graduate research in similar fields.

The survey responses were recorded from 45 investigative experts. These experts included 33 professionals working in the building sector and 12 graduate research students. Since the respondents' population includes experts with different levels of experience in the sustainable construction field, to breakdown this heterogeneity stratified random sampling method [31] was adopted. Stratifying the population into relatively homogenous groups of sampling units reduced sampling error and provided higher precision than simple random samples drawn from the population [32]. Similarly, this approach avoided any skewed results that may occur during sampling of the responses [33]. Thus, the sampling frame was divided into smaller subgroups based on their years of experience in sustainability.

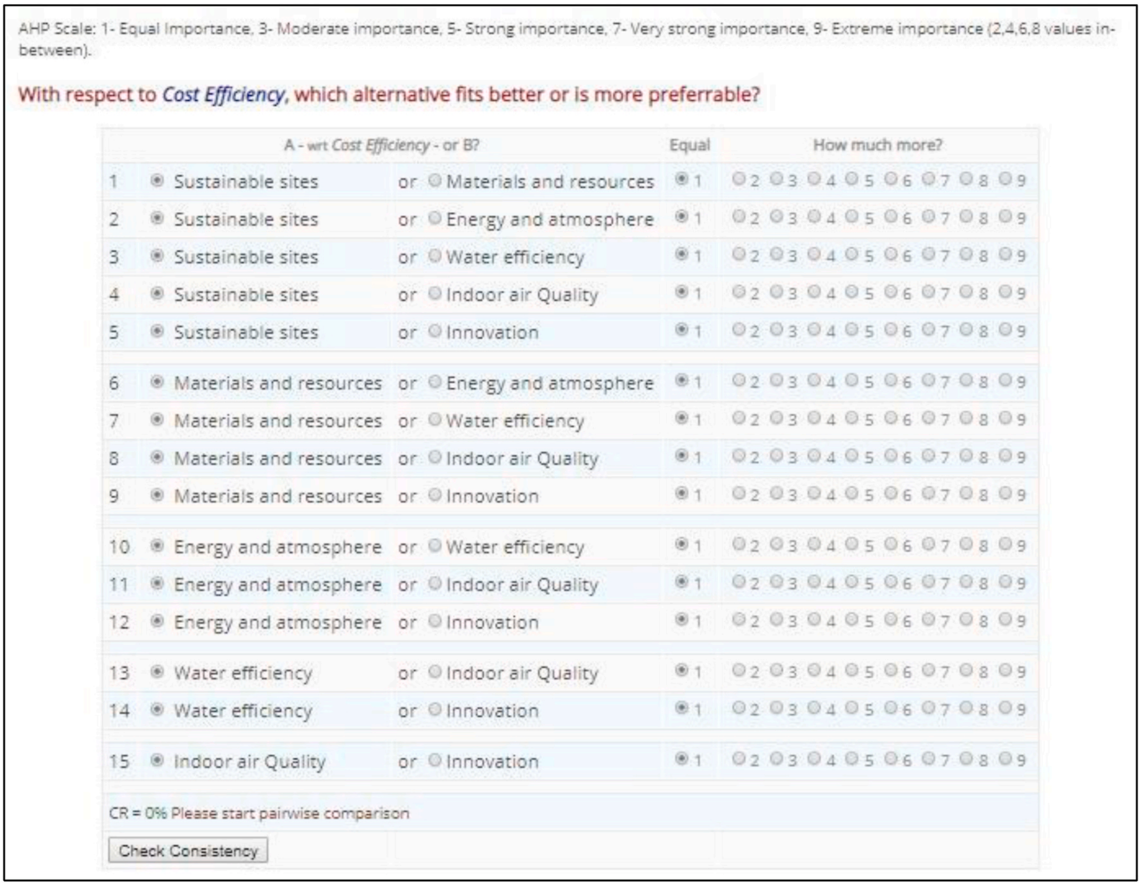


Fig. 7. Snapshot from AHP survey conducted.

Table 2
Local weightages compiled from AHP-OS Survey.

AHP-OS: Local Weightages	COST	ENERGY EFFICIENCY	COMFORT
Sustainable sites	3.40%	5.90%	3.80%
Materials and resources	20.90%	12.00%	10.40%
Energy & atmosphere	21.40%	45.80%	16.50%
Water Efficiency	33.60%	6.10%	8.80%
Indoor air quality	12.20%	15.90%	42.70%
Innovation	8.50%	14.40%	17.80%

The responses were compiled and normalised to calculate the weights for alternatives, which are being described below. Fig. 7 below shows a sample snapshot from the survey input page. It is a snapshot showing the input interface in the survey, which does pairwise check of the alternatives with respect to an attribute (cost efficiency). For instance, in serial number 1, the user is asked to compare whether "Sustainable Sites" or "Materials and Resources" are more important when viewed from a cost-efficiency standpoint. If the user feels improving Sustainable Sites attributes explained in LEED-India is having equal importance with improving materials and resources attributes to get a cost-efficient building, then he/she may opt for "1" as an answer. The user has complete freedom to give importance according to their knowledge and experience. The AHP-OS also calculates the consistency ratio for each hierarchy node using the linear fit approach proposed by Alonso and Lamata [34]. The software identifies the top 3 judgements for which the CR goes higher than 10% and highlights the corresponding pairwise comparisons to the users, allowing them to make necessary amendments [35].

The Local weightings of each alternative with respect to the corresponding criteria calculated by the AHP-OS survey are summarised in Table 2 below. The weightages found from the survey is different from the weightages of each category in LEED-India shown in Table 1. The weightages of each category of LEED-India are the portion of the score each of these categories holds in the total score, which LEED-India provides. In contrast, the weightages calculated by AHP-OS is the importance of each category in helping the building to achieve sustainability with respect to the corresponding criteria considered.

The global weights for the attributes in the second level of the AHP hierarchy are calculated directly from the user inputs on their preferences. Users are asked to prioritise these three criteria through a pairwise analysis similar to AHP. They are asked to prioritise each pair of the criteria on a scale of 10, and these inputs are developed into global weightage using a pairwise comparison matrix. A pairwise comparison matrix expressing the relative values provided by the user, along with the underlying mathematical algorithms and matrixes required for this calculation, was developed as a spreadsheet program. This structure converted the user's responses on their required priorities into weightings of the attributes. The consistency of these inputs from users was analysed using the developed program. Saaty's approach to finding the Consistency ratio (CR) by comparing the consistency index (CI) of the matrix with the Random consistency Index (RI) was adopted [30].

$$CR = \frac{CI}{RI}$$

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

λ_{max} = Eigenvalue for the pairwise comparison matrix
n = Rank of Pairwise comparison matrix/number of criteria

PAIRWISE COMPARISON			
	Cost	Energy efficiency	Comfort
Cost	1.00	3.00	9.00
Energy efficiency	0.33	1.00	5.00
Comfort	0.11	0.20	1.00
Sum	1.44	4.20	15.00

RESULT	
n	3.00
λmax	3.029
CI	0.015
CR	**0.025**
RI	0.58

STANDARDIZED MATRIX				
	Cost	Energy efficiency	Comfort	Weight
Cost	0.69	0.71	0.60	66.9%
Energy efficiency	0.23	0.24	0.33	26.7%
Comfort	0.08	0.05	0.07	6.4%

CI and CR WORKSHEET					
	Cost	Energy efficiency	Comfort	SUM	SUM/Weight
Cost	0.67	0.80	0.57	2.04	3.057
Energy efficiency	0.22	0.27	0.32	0.81	3.026
Comfort	0.07	0.05	0.06	0.19	3.005

Fig. 8. Snapshot from the developed program to Calculate the consistency index.

Please provide your Priorities (weightages)

	Cost vs Energy Efficiency	Cost Vs Comfort	Energy efficiency vs Comfort
Provide relative importance between two criteria. (According to a numerical scale from 1 to 9)	3.000	9.000	5.000

Consistency of your input. (Change your inputs if its "NOT OK")	0.025182306	OK

Value	Interpretation (j vs k)
1	j and k are equally important
3	j is slightly more important than k
5	j is more important than k
7	j is strongly more important than k
9	j is absolutely more important than k

Please provide your required ratings and compliance

ECBC	ECBC+	LEED- INDIA	PLATINUM

ECBC SUGGESTIONS (CONSIDER THE HIGHLITED CRITERIA)

LEED-India suggestions to improve

Fig. 9. A snapshot from the input interface for the second phase.

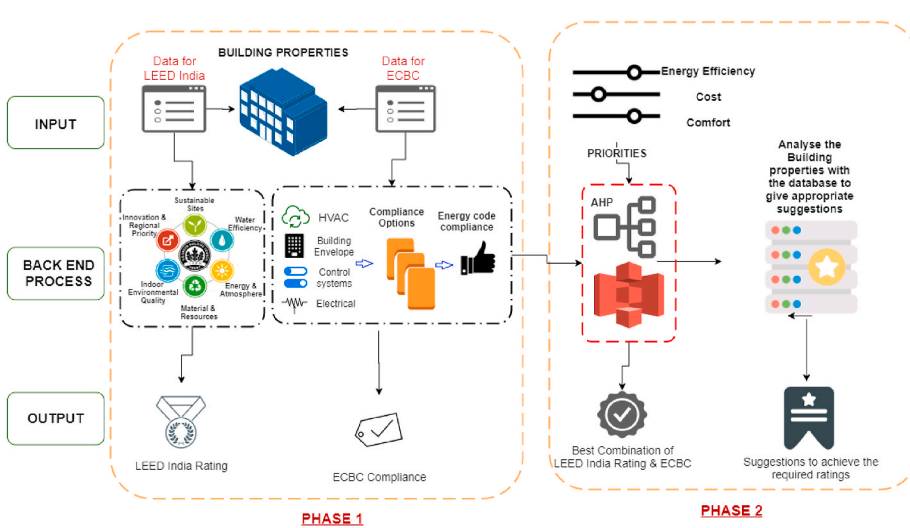


Fig. 10. Complete framework.

Table 3
Salient features of the ITC Green Centre building.

SUSTAINABLE SITES	
Alternate transportation	• Covered storage facilities for bicycles • Shower and changing facilities for bicyclists • Pool cabs with charging spots
Storm Water management	• Implemented recharge pits to ensure zero discharge of stormwater into municipal drainage
Heat Island Effect	• 80% underground parking • More than 75% of hardscape shaded
Light Pollution Reduction	• Light pollution controlled using minimum artificial lighting
WATER EFFICIENCY	
Water-efficient landscaping	• Irrigation by 100% recycled water
Innovative Water treatment	• Provided Fluidized Aerobic Bioreactor sewage treatment plant
Water Use Reduction	• Water Usage reduced by 40%
ENERGY & ATMSPHERE	
Energy	• 51% upgrade from ASHRAE 90. Base standards
Building Envelope	• Autoclaved Aerated Concrete blocks used • Double glazed window with low e-coating • Used 75 mm thick extruded polystyrene roof insulation
HVAC	• Chillers of COP 6.1
Hot water	• Solar thermal technology provided
Ozone Depletion	• CFC, HCFC & Halon free air- conditioning system
MATERIALS AND RESOURCES	
Collection and storage of recyclables	• Segregated recycle bins for different materials available on each floor
Resource reuse	• Refurbished/salvaged building materials from other sites used more than 10%
Recycled content	• Fly ash-based cement and AAC blocks • Acoustic ceilings, Medium Density Fibreboards (MDF) cabinets, etc.
Regional materials	• More than 40% of the materials used are from within 400 miles
Rapidly renewable materials	• MDF boards used for cabinets
Certified wood	• The wood used in the building was certified under the Forest Stewardship Council, US.
INDOOR ENVIRONMENTAL QUALITY	
Tobacco smoke control	• Designated smoking rooms at convenient locations.
CO_2 monitoring	• Sensors to monitor CO_2 levels.
Low emitting materials	• Low VOC levels of adhesives, sealants, and primers used for carpets, woods, and paints.
Daylight and views	• 90% of regularly occupied areas have views of external glazing.
INNOVATION AND DESIGN	
Green Education	• Educated visitors, consultants, construction workers, and employees on sustainability.

Random Consistency Index (RI) = Corresponding index of consistency from large samples of matrixes of purely random judgements, derived from Saaty [30].

A snapshot of the developed spreadsheet program that calculates the consistency of inputs using the pairwise matrix is shown below in Fig. 8. The inputs were considered to be consistent and acceptable if the CR value was calculated to be less than 10% [35]. If not consistent, the input interface highlights the entry as "NOT OK" and asks the user to make amendments. Otherwise, the screen displays "OK," as shown in Fig. 9.

These weightings provided by the users were compiled with the local weights from the survey to determine the priority for all the alternatives in the AHP structure. Based on the priority of each alternative found using this technique, the user is provided with possible improvements to achieve the desired level of rating for the building. The order in which these improvements need to be incorporated and the impact caused in the LEED-India score by each improvement is studied using scenario analysis and is explained later in this paper.

3.4. Input-output interface: phase 2

The snapshot depicting the input interface for the second phase, and the details of the interpretation of scale values is shown in Fig. 9 below. These values are processed by the framework to develop suggestions for improving the sustainability performance of the building using the decision-making technique. The user also can enter a desired compliance/rating level in this phase (e.g., a LEED-India platinum rating), and after getting these details, the framework uses AHP to find the best-suited suggestions.

The framework displays the output from Phase-2 on two different screens. First, the attributes which outperformed against the requirements of attaining the required level of compliance in ECBC are highlighted in the user's input screen itself. Second, the tool also highlights the possible changes available in all the five categories and provides users with the priority to implement their changes to achieve the demanded results. A detailed report comparing the gained and needed LEED-India credits of all categories and the priority order in which the modifications should be done among the categories are also shown on this screen. Fig. 10 below incorporates both the first and second phases of the framework with the detailed input, output, and backend process bifurcations. In the following sections, this framework is validated through a combination of case studies and a sensitivity analysis.

4. Validation and scenario analysis

Phase-1 of this framework is validated using the data collected from two green-rated and ECBC compliant buildings, ITC (Indian Tobacco Company) Green Centre, Gurgaon, India, and Jawahar Nehru Bhavan (JNB), Janpath, New Delhi, India. The former is a Platinum rated green building as per LEED-India certification and is built by ECBC 2007 standards. Meanwhile, the latter holds the badge of being the first ECBC compliant government building with a green building certification as per the LEED rating system.

4.1. Building 1: ITC Green Centre, Gurgaon

ITC Green Centre is the headquarters of the ITC hotel division and is located in the industrial hub of Haryana state in India. This 170,000 square foot office complex obtained the LEED platinum award in 2004 and is considered an ECBC compliant building by TERI (The Energy and Resources Institute). Several green features incorporated in the building have resulted in 53% energy savings, a 40% reduction in potable water use, and 30% less carbon footprint and exceeds ASHRAE 90.1 base case standards by 51% [36]. The salient features incorporated in achieving the platinum rating for ITC Green Centre is summarised in Table 3 below. The complete details of this building are identified from reliable sources [39] and are used to validate the Phase-1 of the framework.

The collected data about the ITC building is fed into the Phase-1 of the framework. As per the ITC portal (2004), ITC Green centre has originally gained a Platinum rating in LEED, i.e., a scoring of 99/110. The framework developed through this study had suggested a very close rating with a LEED score of 95/110. There was about five percent of the inputs needed in the framework, which were not available from the collected sources, and a pessimistic approach is adopted towards these responses, and the minimum or lowest possible responses were entered.

4.2. Building 2: Suzlon One Earth, Pune

As mentioned above, data regarding one more building is used to validate the Phase-1 of the framework, Suzlon One Earth building located at Pune, India. This office building is the campus for the 'world's largest integrated wind turbine manufacturer. It is a three-story building in a plot area of 45,392 square meters and a built-up area of 70865 square meters, including an office complex and corporate learning centre of 3000 employees (Mehta 2013). Suzlon produces about five

Table 4
Salient features of Suzlon One Earth building.

SUSTAINABLE SITES	
Site planning	• Covered construction area to prevent dust pollution • Onsite soil erosion controls adopted • Designed utility corridors along roads and pathways on site
WATER EFFICIENCY	
Water-efficient landscaping	• Reduce landscape water requirement • Minimisation of lawn area • Use of water from non-potable sources
Innovative Water treatment	• Water treatment with RO technology- Max 200LPH • Water treatment plant for Raw water and rainwater harvesting system
Water Use Reduction	• Water Usage reduced by 40% • Efficient water use during construction
ENERGY & ATMOSPHERE	
Energy	• 47% savings
Building Envelope	• Minimal Heat gain: 40% better than ASHRAE 90.1 and ECBC 2007 standards. • Natural ventilation provisions in transition spaces • More than 90% of daylight spaces
HVAC	• The system gave the flexibility of a variable refrigerant volume system • Direct-Indirect evaporative cooling
Hot water	• Solar thermal technology provided
MATERIALS AND RESOURCES	
Low energy materials	• The reduced carbon footprint for more than 70% of materials used in the interiors
Resource reuse	• Refurbished/salvaged building materials from other sites used more than 10%
Recycled content	• 15% replacement of cement with Fly ash
Green Materials	• 37% reduction in concrete quantity by the usage of post-tension slab • 50% reduction in the amount of steel by using a post-tension slab. • Siporex fly-ash blocks used for insulation
INDOOR ENVIRONMENTAL QUALITY	
Tobacco smoke control	• Designated smoking rooms with separate exhausts at convenient locations.
Low emitting materials	• Low VOC levels of adhesives, sealants, and primers
Daylight and views	• 90% of regularly occupied areas have views of external glazing.
Noise levels	• Acceptable indoor and outdoor noise levels.
INNOVATION AND DESIGN	
Green Education	• Educated visitors, consultants, construction workers, and employees on sustainability.

percent of its total annual energy usage by building integrated photovoltaic panels and wind turbines. Suzlon also generates the remaining 95% through their off-site wind turbines, thus making Suzlon one earth a net-zero building. The building design provides enough daylighting, proper energy-efficient measures, sewage grey water recycling, and rainwater harvesting techniques (Bonde 2018). The detailed report on the salient green features incorporated in the building is shown below in Table 4.

Table 6
Ranks for categories achieved for respective cases considered.

RANKS	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
SUSTAINABLE SITES	6	6	6	6	5	5
MATERIAL & RESOURCES	3	3	3	3	3	3
ENERGY & ATMOSPHERE	2	1	1	2	2	1
WATER EFFICIENCY	5	5	5	5	6	6
INDOOR AIR QUALITY	4	4	4	4	4	4
INNOVATION	1	2	2	1	1	2

Suzlon One Earth is one of the greenest office campuses in the world with the achievement of Platinum certification in LEED-India along with a GRIHA five-star certifications. Suzlon building Project also complies with the energy standards as per ECBC 2007 [40] and has achieved a five-star certificate with GRIHA. With the incorporated techniques, Suzlon One Earth achieved LEED-India Platinum certification scoring 57 out of 69, which was an old scoring mechanism of LEED- India. The framework developed in this study used the latest version of LEED-India, where the maximum credits a building can achieve is 110. All the data available from the different sources [41], [42], [37], [40] were organised and made useful as input data for the developed framework. New attributes that were not measured in earlier versions were considered to the pessimistic scale. Compiling all the input data, the tool rated Suzlon building with '''ECBC' compliance and platinum certification in LEED-India, achieving 82 out of 110. Thus, this case study strengthened the validity of the developed framework with an accuracy of 90%.

4.3. Scenario analysis

As previously mentioned, Phase-2 of this framework aims at producing suggestions to improve the performance of the assessed building according to user preferences and requirements. This phase of the developed system is also validated, considering all plausible scenarios. The scenario analysis is conducted to observe and analyse all possible outcomes from the already LEED rated buildings, and by following its sensitivity to different scenarios. This analysis is done over a building with a silver rating in the LEED-India rating system, i.e., a score of 50 out of 110. The developed framework obtains the local weights for the AHP analysis from the survey done, and the user directly enters the global weights of the categories in the AHP hierarchy. The scenario analysis examined all plausible ranges of priority for cost efficiency, energy efficiency, and comfort that the user could provide. The six cases examined for this study with maximum, minimum, and average values for all

Table 5
Six cases considered for the scenario analysis.

Cases	Cost Efficiency	Enegry Efficiency	Comfort
Case 1	17	34	49
Case 2	17	49	34
Case 3	34	49	17
Case 4	34	17	49
Case 5	49	17	34
Case 6	49	34	17

Table 7
Validation for phase 1, summary.

CASES	Actual Scenario		As per Tool Result		% Error
	LEED India Score	LEED Rating	LEED India Score	LEED Rating	
ITC Green Centre, Gurgaon	99/110	Platinum	95/110	Platinum	4.0%
Suzlon one earth	57/69*	Platinum	82/110	Platinum	9.76%

(* The building was rated in an older version, V2.2 of LEED India; thus the maximum score is 69).

the three criteria are shown below (Table 5).

AHP structure in the framework produced different ranks of priorities for the categories with the difference in the scenarios employed. The six cases considered, and the positions obtained by the criteria in each case is shown in the snapshot below (Table 6). These rankings represent the order through which the green-oriented strategies to be executed for LEED-India score betterment. Based on these rankings and the adapted building parameters provided in phase 1 inputs, the tool develops a summary for the user providing possible suggestions for improvements. This summary also suggests the likely order in which these improvements can be incorporated and the corresponding impact in the LEED-India score.

5. Results

The developed tool discussed in this paper, through its first phase, breaks down the exhaustive approach of sustainability assessment methods into a digitised, more convenient, and user-friendly platform. The score and compliance achieved in the case studies were compared against the actual score achieved in LEED-India and the compliance level received in ECBC. The tool succeeded in making the results with an error rate of less than 10%, as shown in Table 7 below.

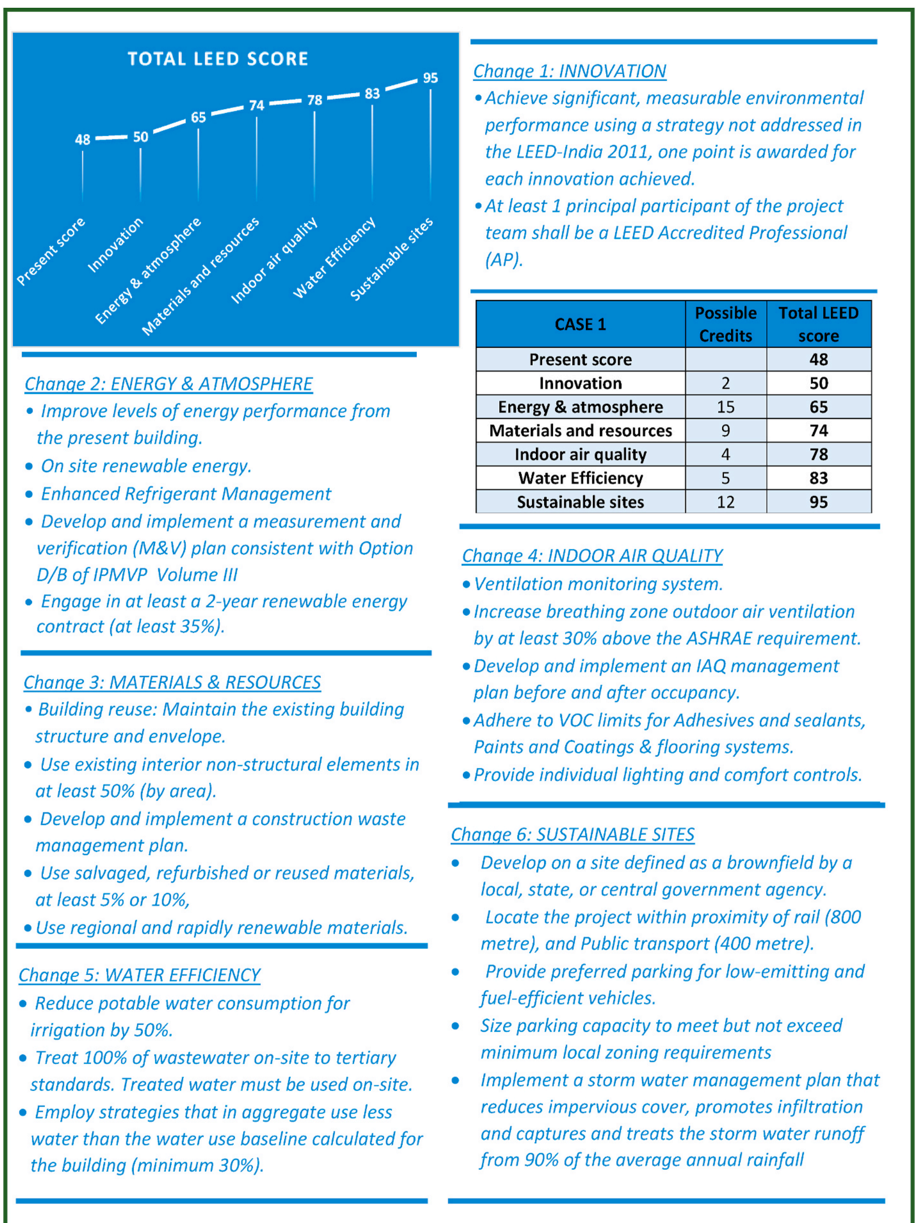


Fig. 11. Output screen for Case 1 of the scenario analysis.

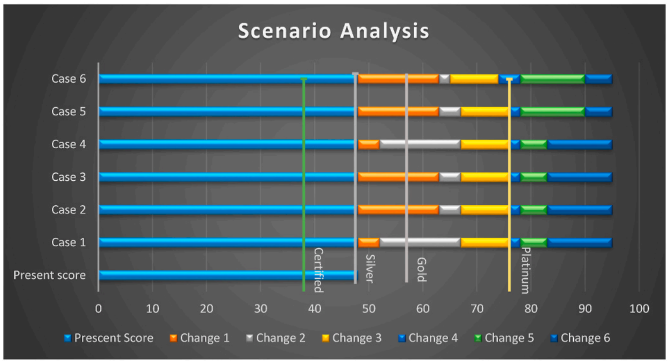


Fig. 12. The framework developed results for each case considered.

The second phase of the tool considers the interests of the user and suggest improvements to achieve the required rating and ECBC compliance, adhering to the user's definition of sustainability. For this, the tool develops a detailed summary for the project based on the achieved score in Phase 1 and the priority requirement provided by the user on Comfort, Cost, and Energy Efficiency. Fig. 11 below shows a typical case in which the rankings could be improved in Case 1 of Scenario analysis discussed above by following the specific suggestions through the ranks. In Case 1, the first rank is for the innovation, and the two suggestions are provided to improve the currents score of 48–50. Similarly, other changes and the detailed recommendations are also shown in Fig. 11, through which the LEED-India score could be raised to 95 from 48.

A detailed assessment of all the cases considered in the scenario analysis with the projection of possible results is shown in Fig. 12. The depiction shows the required changes and the order in which it is to be done for achieving the performance needed for building for each case considered. The lines cutting the column bars also show the score necessary to achieve higher ratings such as Silver, Gold, and Platinum. This analysis has accommodated most of the preference scenarios. It provides a handy approach for the various building stakeholders to increase the sustainability levels of proposed building designs.

6. Conclusions and discussion

Building sector accounts for an enormous amount of resource exploitation, energy use, and greenhouse gas emissions. Sustainable construction is becoming increasingly desirable and profitable with the rising demand for greener building options within the construction market [38]. Even after understanding the need for a sustainability-oriented approach for building construction, current regulatory and assessment techniques face significant impediments in its practice due to their shortcomings examined through this study. Building performance assessment methods mainly lack acceptance due to its complexity, inflexibility, and lack of consideration of weighing systems. Simultaneously, the regulatory system falls below with the single criteria approach along with other intricacies, and still faces the question of acceptance throughout the country.

The optimization framework developed in this study analyses building environmental performance and considerably reduce the complications in using these regulatory systems. Rather than concentrating on the conventional approach of reducing environmental impacts, this study offers a data-driven and user-friendly framework which grants the user the freedom to do several iterations of assessments and choose the best possible method for satisfying the need for a greener building. This system also utilises the information collected from the users through a structured analytical hierarchical process to generate code-compliant building design strategies.

The second phase of this research, using AHP, guides the users to achieve their required level of performance without sacrificing their priorities in cost, comfort, and energy efficiency. The developed tool also defines the sequence and impact of each suggested improvement. However, the cost associated with these improvements are outside the scope for this study and is considered to be performed as a future scope. Similarly, even though the described tool succeeded in predicting the credits the building can gain in LEED-India with reasonable accuracy, the small percentage error found to occur in the results is accepted as a potential limitation for this approach. However, in a developing country such as India with substantial avenues for promoting sustainable development, this discussed framework can help the widespread adoption of various sustainable techniques in existing building retrofit and future buildings stock development.

CRediT author statement

Amarnath Payyanapotta: Conceptualization, Methodology, Validation, Formal Analysis, Writing- Original draft preparation **Albert Thomas** Supervision, Writing- Reviewing and Editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] P. Dewick, M. Miozzo, Sustainable technologies and the innovation–regulation paradox, Futures 34 (9–10) (2002) 823–840.
[2] S. Roaf, Benchmarking the 'sustainability' of a building project, Assessing building performance 1 (2005).
[3] C.J. Kibert, Sustainable Construction: Green Building Design and Delivery, John Wiley & Sons, 2016.
[4] R. Rawal, P. Vaidya, V. Ghatti, A. Ward, S. Seth, A. Jain, T. Parthasarathy, Energy code enforcement for beginners: a tiered approach to energy code in India, in: ACEEE Summer Study on Energy Efficiency in Buildings, vol. 3, 2012, pp. 313–324 (Cbre 2011).
[5] R. Rawal, P. Vaidya, V. Ghatti, A. Ward, S. Seth, A. Jain, T. Parthasarathy, August. Energy code enforcement for beginners: a tiered approach to energy code in India, in: ACEEE Summer Study on Energy Efficiency in Buildings, vol. 3, 2012, pp. 313–324.
[6] R.M. Smith, "Green" building in India: a comparative and spatial analysis of the LEED-India and GRIHA rating systems, Asian Geogr. 32 (2) (2015) 73–84.
[7] A. Elnokaly, M. Vyas, A cross case investigation of sustainability assessment tools of the LEED, BREEAM and GRIHA, in: Transitions to Sustainable Societies: Designing Research and Policies for Changing Lifestyles and Communities (IAPS 23 Conference), Timisoara, Romania, 24 June-27 June 2014, 2014, June.
[8] J.K.W. Wong, J.K. San Chan, M.J. Wadu, Facilitating effective green procurement in construction projects: an empirical study of the enablers, J. Clean. Prod. 135 (2016) 859–871.
[9] A.P.C. Chan, A. Darko, E.E. Ameyaw, Strategies for promoting green building technologies adoption in the construction industry—an international study, Sustainability 9 (6) (2017) 969.
[10] G.S. Vyas, K.N. Jha, Identification of green building attributes for the development of an assessment tool: a case study in India, Civ. Eng. Environ. Syst. 33 (4) (2016) 313–334.
[11] G.K. Ding, Sustainable construction—the role of environmental assessment tools, J. Environ. Manag. 86 (3) (2008) 451–464.
[12] H.H. Ali, S.F. Al Nsairat, Developing a green building assessment tool for developing countries–Case of Jordan, Build. Environ. 44 (5) (2009) 1053–1064.
[13] Q. Qian, E. Chan, A. Khalid, Challenges in delivering green building projects: unearthing the transaction costs (TCs), Sustainability 7 (4) (2015) 3615–3636.
[14] G. GRIHA, Acronyms and Abbreviations. Climate Change and Cities: First Assessment Report of the Urban Climate Change Research Network, 2011, p. 275.
[15] Bureau of Energy Efficiency, ECBC residential, Accessed on 18th December 2019, https://beeindia.gov.in/content/ecbc-residential, 2019.
[16] D.T. Doan, A. Ghaffarianhoseini, N. Naismith, T. Zhang, A. Ghaffarianhoseini, J. Tookey, A critical comparison of green building rating systems, Build. Environ. 123 (2017) 243–260.
[17] S.H. Alyami, Y. Rezgui, Sustainable building assessment tool development approach, Sustainable Cities and Society 5 (2012) 52–62.
[18] V.I. Soebarto, T.J. Williamson, Multi-criteria assessment of building performance: theory and implementation, Build. Environ. 36 (6) (2001) 681–690.
[19] C. Tisdell, Project appraisal, the environment and sustainability for small islands, World Dev. 21 (2) (1993) 213–219.

[20] P. Nijkamp, P. Rietveld, H. Voogd, Multicriteria Evaluation in Physical Planning, vol. 185, Elsevier, 2013.
[21] R. Janikowski, R. Kucharski, A. Sas-Nowosielska, Multi-criteria and multi-perspective analysis of contaminated land management methods, Environ. Monit. Assess. 60 (1) (2000) 89–102.
[22] D. Crawley, I. Aho, Building environmental assessment methods: applications and development trends, Build. Res. Inf. 27 (4–5) (1999) 300–308.
[23] R.J. Cole, Building environmental assessment methods: clarifying intentions, Build. Res. Inf. 27 (4–5) (1999) 230–246.
[24] D. Crookes, M. de Wit, Environmental economic valuation and its application in environmental assessment: an evaluation of the status quo with reference to South Africa, Impact Assess. Proj. Apprais. 20 (2) (2002) 127–134.
[25] T.L. Saaty, The analytic hierarchy process McGraw-hill New York, Agric. Econ. Rev. 70 (1980).
[26] K.D. Goepel, Implementation of an online software tool for the analytic hierarchy process (AHP-OS), International Journal of the Analytic Hierarchy Process 10 (3) (2018).
[27] M.J. Skibniewski, L.C. Chao, Evaluation of advanced construction technology with AHP method, J. Construct. Eng. Manag. 118 (3) (1992) 577–593.
[28] M.C. Tam, V.R. Tummala, An application of the AHP in vendor selection of a telecommunications system, Omega 29 (2) (2001) 171–182.
[29] R. Ramanathan, A note on the use of the analytic hierarchy process for environmental impact assessment, J. Environ. Manag. 63 (1) (2001) 27–35.
[30] T.L. Saaty, Decision-making with the AHP: why is the principal eigenvector necessary, Eur. J. Oper. Res. 145 (1) (2003) 85–91.
[31] A.S. Acharya, A. Prakash, P. Saxena, A. Nigam, Sampling: why and how of it, Indian Journal of Medical Specialties 4 (2) (2013) 330–333.
[32] C. Tong, Refinement strategies for stratified sampling methods, Reliab. Eng. Syst. Saf. 91 (10–11) (2006) 1257–1265.
[33] P.S. Levy, S. Lemeshow, Sampling of Populations: Methods and Applications, John Wiley & Sons, 2013.
[34] J.A. Alonso, M.T. Lamata, Consistency in the analytic hierarchy process: a new approach, Int. J. Uncertain. Fuzziness Knowledge-Based Syst. 14 (2006) 445–459, 04.
[35] K.D. Goepel, Implementation of an online software tool for the analytic hierarchy process—challenges and practical experiences, Implement. Online Softw. Tool AHP Chall. Pract. Exp 10 (2017) 1–20.
[36] USGBC, ITC green centre, USGBC projects. https://www.usgbc.org/projects/itc-green-centre, 2014. (Accessed 20 February 2019).
[37] J. Yudelson, Green Building A to Z: Understanding the Language of Green Building, New Society Publishers, 2007.
[38] WGBC, The Benefits of Green Buildings, WGBC, 2016. https://www.worldgbc.org/benefits-green-buildings. (Accessed 29 August 2018).
[39] https://www.usgbc.org/projects/itc-green-centre, 2019. (Accessed 20 February 2019).
[40] T Joshi, S Joshi, Green Buildings: A Need of Future Cities, In Proceedings 2019: Conference on Technologies for Future Cities (CTFC) (2019).
[41] H.S. Mehta, Vishal Porwal, Green building construction for sustainable future, Civil and environmental Research, 3 (6) (2013) 7–13.
[42] Rasika Bonde, et al., Assessment of Green Building through GRIHA Rating Tool and its Implementation, GRD Journals- Global Research and Development Journal for Engineering 3 (4) (2018) 32–35.