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Research article

A novel index to predict the cost of green resilient buildings

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ABSTRACT

Climate change impacts the demand of the construction industry to reduce its carbon footprint while increasing the resilience of the buildings. This twofold need emphasises better understanding and cost prediction of green resilient buildings based on their 'resilience' and 'sustainability', which is very limited or based on obsolete perceptions and stereotypes. This study presents a novel index to predict the cost of converting a conventional building to a green-resilient building. In this study; twenty factors based on comprehensive market research have been analysed both quantitatively and qualitatively. An economic impact model has been developed for the cost prediction of green resilient buildings through a novel Green Resilient Building Index, based on sustainability and resilience factors, and the cost of conventional buildings. It has been observed that on-ground construction cost and predicted values fall within 10 % of the 1:1 line validating the precision and confidence level of the research data. Single-factor analysis of variance showed the acceptable precision of the results at a confidence level of 95 %. Nevertheless, this study envisions supporting the professionals and policymakers to develop a sustainable construction industry.

1. Introduction

Stakeholders of the built environment are actively responding to policies focusing on enhancing sustainability [1,2] and resilience [3]. This trend is because the construction industry plays a huge role in polluting the environment [4] while being responsible for the vulnerability of the communities in the event of climate change-induced disasters [5]. This demands the construction industry to not only be sustainable but also resilient i.e. the construction industry should reduce the emissions of greenhouse gases (GHGs) while reducing its vulnerablity to the climate induced natural diasters. Hence, preserving the natural environment has emerged as a vital concern for the building industry, needing excessive efforts to transform the construction sector into green and resilience-enhancing building designs. Green sustainability and resilience of buildings should inevitably be integrated at all levels through sustainable development systems in urban centres [6]. Global warming is one of the most pressing issues the global community faces due to greenhouse gases (GHG) emitted by the construction industry [7] which stresses the importance of sustainable green buildings. Green buildings are required to be resilient for the survivability of the occupants in extreme conditions to cope with environmental vulnerabilities and disasters [8] which stresses the importance of sustainable green buildings. On the other hand, while sustainability is

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progressing in research and development, climate-induced catastrophes are also becoming more frequent requiring more attention towards the resilience of sustainable buildings to preserve the natural environment [9]. Hence, to attain the Sustainable Development Goals 2015, it is vital for the communities to enhance their resilience by focusing on their preparedness and adaptation to natural hazards by enhancing their quality of construction and reducing greenhouse gas emissions [10].

Green transformation, i.e., converting a conventional building into a green resilient building will involve several factors which will increase its resilience of the green building. It is essential that the nexus of these parameters are particularly realized and special attention is to be given to the sustainability and resilience of green building. Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Star, Green Mark and GREENSL rating system identify the resilient parameters in the green and sustainable buildings as shown in the conceptual diagram in Fig. 1. There are several factors which can enhance the resilience and sustainability of green buildings. Some of the factors extracted from these green building standards include landscape management, external lighting, natural ventilation, on-site rain collection, daylighting, stormwater design, rainwater harvesting, natural ventilation, erosion and sediment control, recycling materials, sustainable drainage, building orientation and sustainable drainage techniques. These factors not only increase the sustainability of green buildings but also their resilience. The passive design approach and reducing the initial damage to the building system will help increase the resilience of green buildings [11].

The construction industry ranks first among other industries in total CO_2 (38 %) emission and total energy use (35 %), whereas in USA, buildings use 14 % of portable water, 72 % of electricity and generate 30 % of the total waste [12] and in European Union, 75 % of the building stock is "energy inefficient" [13].

US Green Building Council (USGBC) Washington (2003) [13] states that the increased role of green buildings can lead to substantial benefits for the environment by reducing greenhouse gas emissions: carbon dioxide emissions reduced by 35 %; reduction in the use of total energy by 30–50 % and 70 % savings on waste output [13].Green buildings play a vital role in achieving sustainable development goals by reducing gas emissions into the environment by increasing the energy efficiency of the building systems and reducing the cost of internal cooling and heating of the building using fuel; hence reducing the negative environmental effects of these buildings such as reduced waste output, less energy consumption and lesser CO_2 emission [14]. Besides environmental benefits, green buildings also reduce the need for maintenance and improve indoor air quality and ambient temperatures due to which communities are shifting towards green buildings [15,16]. However, this transition from conventional to green buildings is a bit slow in developing countries due to a wide range of constraints [17].

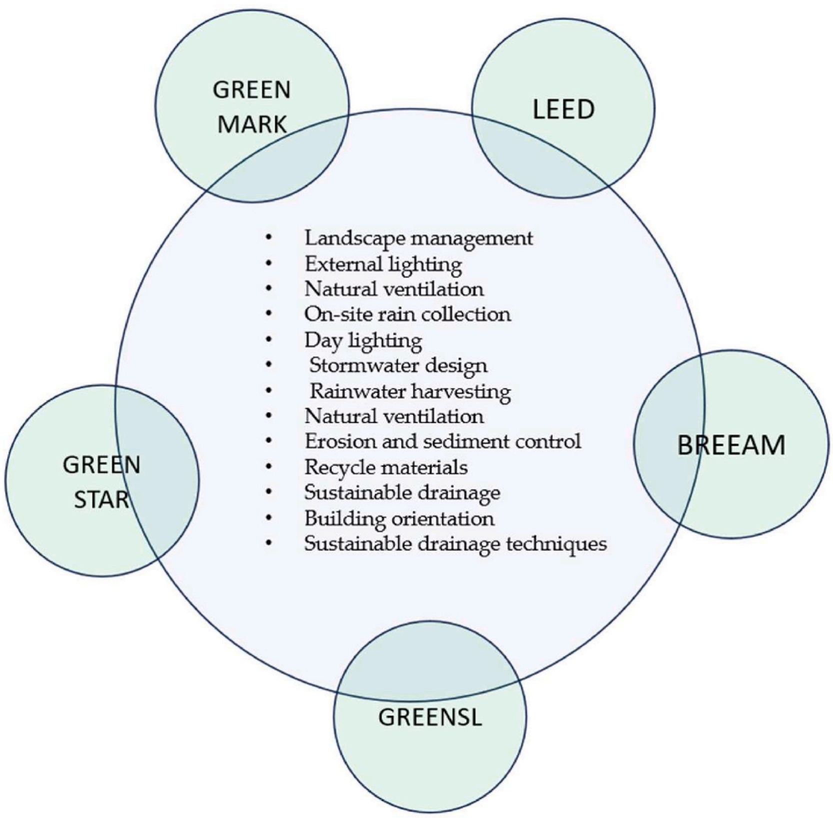

Fig. 1. Factors affecting the resilience and sustainability of green resilient buildings.

1.1. What is resilience?

Climate change adaptation and disaster mitigation emphasise the importance of resilience in sustainable development [18,19] while focusing on the tensions between the two concepts [5]. According to Ref. [5] the main idea of sustainability is to minimise the deteriorating impacts on the environment to avoid changes; the idea of resilience is the adaptation to change. In 1973, literature mentioned resilience as “a measure of the determination of systems and their tendency to tackle change and disturbance and still maintain the same relations between populations or state variables” [20] which now is defined as a response to shocks, extreme events and catastrophic events [21]. Prior researchers have defined resilience in a variety of ways. For instance Ref. [22], defined resilience as the “capacity to persist during change, and evolve with ever-changing scenarios” [23]. defined resilience as the “system’s ability to counter disturbance and recover while performing essentially the same function, structure, and identity”. Zhao et al. [24] define resilience as “the ability of a residential structure to reduce industrial risk; and assist vulnerable people, organizations, and systems to persist.” Hence, these definitions focused on adaptability in cases of extreme events, however, despite the wide range of applications there is no one definition of resilience [25]. The definition of resilience may be very different for an insurance agent than it is for an urban planner [26].

1.2. What is sustainability?

Similarly, sustainability on the other hand is also defined in a variety of ways [27]. Some researchers define it as – “to continue the current situation and to not vanish” [28]. Hence, sustainability can be referred to as the ability of a system to maintain its current state [5]. [29] also define sustainability as “something ensuring the well-being of communities and environment” [29]. In addition to this, sustainability can also be explained as the longer a system can be maintained the more sustainable it is [27]. [30] defined sustainability as “the ability to maintain specified qualities of human well-being, social equity, and environmental integrity”. In 1994 [31], defined sustainable construction as “… establishing and operating a healthy built environment based on efficent use of resources and ecological design”. Similarly, The U.S. Green Building Council (1993) through Leadership in Energy and Environmental Design categorizes sustainability in building practises and design in location and transportation, sustainable site, efficiency of water use, energy and atmosphere, material and resources, quality of indoor environment, innovation and priority of the region.

1.3. Various relationships between sustainability and resilience

Past literature suggests several different relationships between sustainability and resilience. Some researchers perceive both concepts as two aspects of the same phenomenon while others see them lying in different dimensions [29] because of the absence of concrete definitions of both concepts and due to some assumptions, methods, socioeconomic, structural and life cycle analysis [32,33] state that both phenomena deal with the survivability and persistence of the system in response to shock [34]. consider sustainability and resilience as interchangeable concepts which are also synonymous [35]. stated that “a resilient socio-ecological system is same as a region that has socio-economic and ecological sustainability.” [36] considered resilience as a suitable way to think of sustainability in social and natural systems. Others view resilience as a precondition for sustainability. For instance [37]; stated that "[…] only those ecosystems are sustainable in which life-support ecosystem is resilient" [38]. stated that "[a] development strategy is not sustainable without resilience" [39]. mentioned that "reinforcing the ability of societies to handle resilience is vital for sustainable development." [40] are convinced that “in hazard-prone regions, sustainability and resilience are related to each other against natural hazards.” [27] found three framework relationships between sustainability and resilience: resilience as a subset of sustainability (i.e. resilience as an essential portion of sustainability), sustainability as a subset of resilience (i.e. increasing sustainability makes the system more resilient) and sustainability and resilience as distinct objectives (i.e. Both concepts are separate yet complimentary [27]. Table 1 below shows the contrast between resilience and sustainability.

Fig. 2 shows the relationships between sustainability and resilience. (a) shows sustainability as a subset of resilience, (b) shows resilience as a subset of sustainability, (c) shows resilience being equal to sustainability and (d) shows that resilience and sustainability do not depend on each other and are distinct.

Previous researchers mostly only compared the cost of green buildings with the conventional ones; however, the cost model presented in this paper uses the composite effects of “sustainability” and “resilience” to predict the cost of the green resilient building. These models are user-friendly and can be directly implemented in the construction market for onsite decisions by developers and policymakers. Moreover, this study focuses on investigating the factors affecting the resilience and sustainability of green resilient buildings to calculate GRBI and investigate how this impacts the cost of green resilient buildings in comparison to conventional

Table 1
Contrast between resilience and sustainability.

Target	Resilience	Sustainability
Goals	Adaptation to environmental hazards and self-organization	Environmental conservation
Assumptions	Disturbance	Stability
Objectives	Adaptability, Redundancy, and performance in extreme event	Management of resources, disaster mitigation
Research focus	Climate change, disaster management	Exploitation of resources
Emphasis	Use of entire capacity	Dependence on global standards

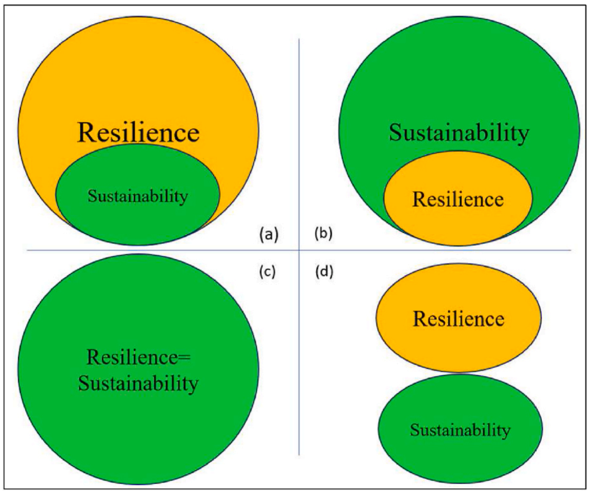

Fig. 2. Shows the relationships between sustainability and resilience.

buildings. Hence the users will not only be able to estimate the cost impact of constructing a green resilient building but will also be able to understand the factors impacting the GRBI of their structure and will estimate the level of resilience and sustainability in the building.

In essence, the general public is becoming more conscious about their carbon footprint and feels less safe in the wake of climate change-induced disasters. As a pertinent concern across the globe, several questions may arise in one's mind; namely, (1) Will my house be able to stand the next flood despite being sustainable? (2) How are the sustainability and resilience of my house related? and (3) Do I need to be greener to prevent global warming or resilient to face the threats posed by climate change? The subject and novelty of this study focuses on investigating the answers to these questions. Accordingly, the factors affecting the resilience and sustainability of green resilient buildings to calculate GRBI and investigate how this impacts the cost of green resilient buildings in comparison to conventional buildings. Hence the users will not only be able to estimate the cost impact of constructing a green resilient building but will also be able to assess the GRBI of their structure and estimate the level of resilience in the building and its cost impact.

2. Prior research

Despite all the positives that green buildings can do to protect the natural environment, there is a lot of scepticism in various quarters about green buildings. Building developers need to ponder more on the effectiveness of the green building market. More data and analysis **are** needed to ensure the economic benefits of green buildings for which extensive planning, design and performance in the line of resilience is considered a significant task [41]. Several researchers have thoroughly studied the effectiveness of green buildings considering their economic, social and environmental impacts [42] studied the impact of green buildings in Kuwait in which a conventional building was transformed into a green building concluding that conversion was environment friendly as it reduced greenhouse gas emissions (GHG) and waste output and the cost saving also increased besides enhancement of air quality. Therefore the data on which people can make informed decisions, must be authentic and readily available such as green building rating systems [43] which have been compared and contrasted by several previous researchers [44,45] stated that stakeholders acceptance to change and the cost related barrier are the biggest hindrance for the proliferation of green buildings [17]. also studied the significant barriers to green procurement in real estate development and found that little marketing benefits and lack of incentive policies are the biggest barriers [46]. also studied the barriers to sustainable construction in Malaysia and found the cost related barriers to be the biggest hindrance for the popularity of green buildings. The cost of green buildings and lack of financial benefits are considered crucial in the design of green buildings [47]**.**

In the wake of climate change and shortage of resources, a lot of researchers are now focused on how communities can be made resilient besides being sustainable because communities in the near future are expected to face an increased number of climate change-induced natural disasters making it essential for the communities to focus on resilient, green, sustainable and smart growth [48]. Although there exists some difference in the definition of building resilience [49,50] it is generally viewed as the ability to return to the natural state after a shock [51] by adaptive and flexible abilities [3]. Some researchers have also worked on community resilience [52–54].

Other researchers suggest that higher cost is considered as one of the most important critical factors for the construction of green buildings in the U.S., Canada, and Australia [45]; in Malaysia [19]; in Romania [55]; in Hong Kong [47] and in Finland [56] while many focused on the positive health-related positive aspects of green infrastructure and their societal impacts [57–70].

In this study the focus is on the resilience of the building unit which contributes towards the urban resilience [71–73] by finding an intricate balance between centralization, decentralization and diversity and standardization [74]. LEED, BREAM and CASBEE are some of the standards which provide a systematic approach to encourage a sustainable green environment in USA, UK and Japan respectively and are based on several environmental factors to achieve the goal of healthier and efficient building models [11]. Although occupants in the green building show greater satisfaction about indoor air quality, resilience has not been frequently quantified [75]. Sustainable and green tranformation to green resilient buildings offer an holistic integration of environmentalism and protection against shock, therefore in a sense, efforts to enhance the sustainability by improving energy efficiency and reducing dependency of external resources, will increase the resilience of the buildings [76]. However in some cases sustainability and resilience may compete with each other as some of the current policies do not support resilience [5]. Therefore in order to combat the challenge of sustainablity and resilience researchers are working on the green resilient buildings which will enhance sustainability while increasing the resilience of the buildings [5].

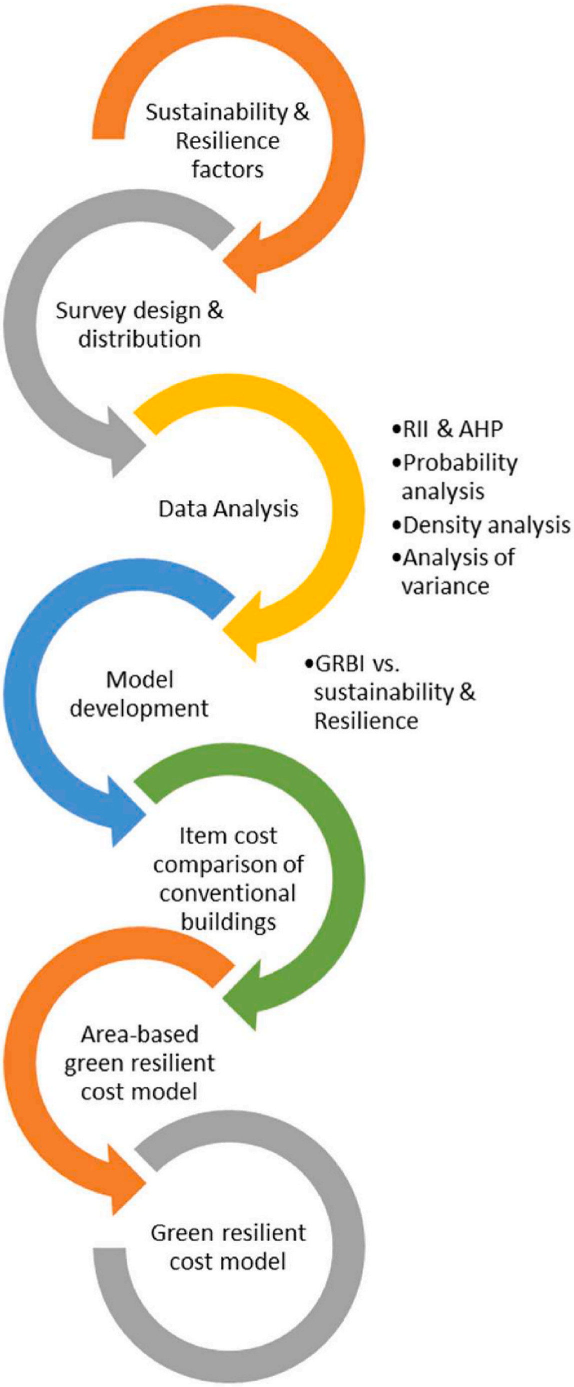

Fig. 3. Methodology involved in this study.

Green resilient buildings aim to add both in the sustainabity and resilience characteristics of the buildings and hence the society. In this study; green resilient buildings are considered to be the unit of sustainable and resilient communities which are of fundamental importance to combat climate change and its extreme events. Conventional to green resilient buildings requires a change in human behaviour and a shift in the consumer psychology which are affected by understanding of the green resilient transformation, business models and incentives offered by the government. Several researchers in the past have studied the interaction of sustainability and resilience, however in most of the cases these researchers have used indirect empirical approaches based on secondary assessments such as literature review, and building code analysis [5].

3. Materials and methods

A survey was conducted to investigate the impact of various factors on the cost of Green Resilient buildings using online Google forms and in-person questionnaires. Those who could not access the internet to fill out the questionnaire were personally called to their offices or were reached out using telephones and WhatsApp. This is a mix of qualitative and quantitative research methods. The analysis of the gathered data involves a technique carried out through multiple entities including the organizational identities, systems, and employees along with a literature review and survey. The survey questions were designed for the stakeholders potentially involved in the design, use and business of construction. The twenty factors have been compiled into two main groups based on the market research having weights ranging from 1 to 9, the higher the score the higher the impact of that factor on the cost of the green building. Elements of this adopted knowledge-based theory consist of the.

1. Selection of factors that affect the cost of the green and resilient building
2. Conducting surveying to investigate the impact of the factors on the cost of the green resilient building
3. Analysis of Variance (ANOVA), density and cumulative frequency on collected data
4. Relative importance index (RII) and Analytic Hierarchy Process (AHP) analysis

The flowchart of the methodology for this study is shown in Fig. 3.

3.1. Selection of factors

A preliminary survey was conducted asking people what factors they considered to have the most impact on the cost of Green Resilient Building. A total of 921 people were approached using online and physical forms and 901 responses were obtained. Fig. 4 shows the results obtained. All the factors (influencers) that had more than 50 % response in the survey were selected for this study. These results were the basis of the questions formed for the determination of RII for sustainability and resilience. Hence, twenty factors

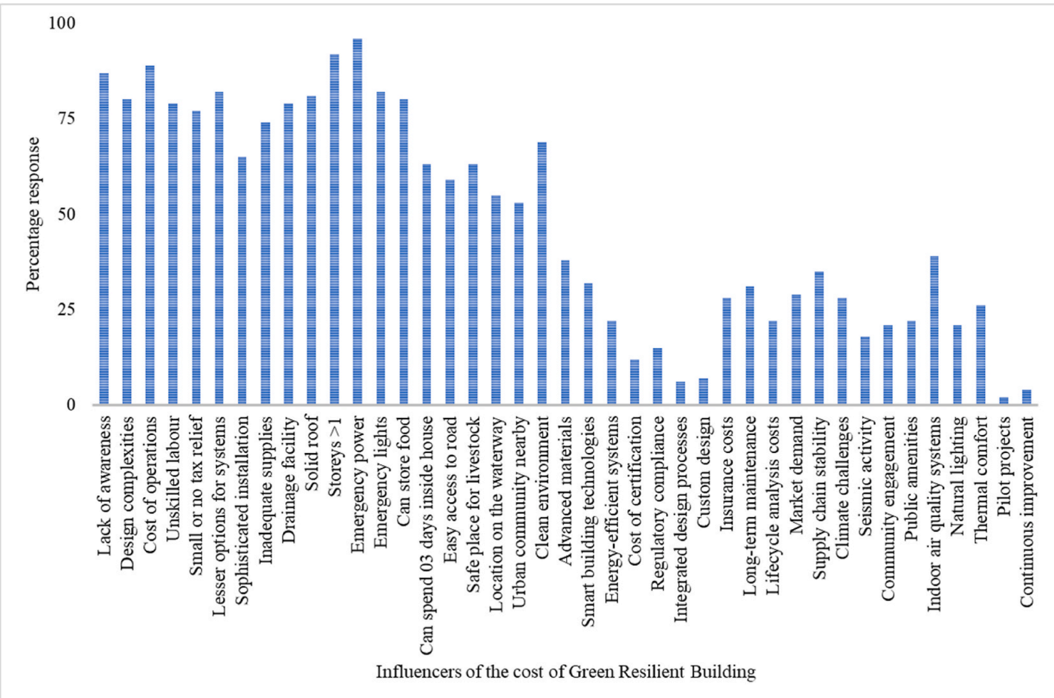

Fig. 4. Response of the preliminary survey.

having strong economic and performance impact on the green resilient buildings which were categorized into sustainability and resilience of the building to provide a green resilient building index (GRBI) having a 9-point linkert scale. The factors comprising lack of awareness, design complexities, cost of operations, unskilled labour, small or no tax relief, lesser options, sophisticated installations, inadequate supplies, drainage facilities, solid roof, storeys >1, emergency power, emergency lights, food storage, 03 days shelter, easy assess to the roads, location of the waterways, nearby community and clean environment.

3.2. Conducting survey

The factors were selected based on the market research and literature review [L. Shen, 17] and questionnaires were sent to 314 professionals out of which 250 responded to collect data from the population sample. The respondents come from diverse backgrounds to accommodate the diversity of views about green buildings. 80 out of the 250 respondents (32 %) are related to the field of Civil engineering, while 26 % and 18 % are related to Mechanical and HVAC engineering respectively. 12 % per cent respondents were working in teaching and research while 13 per cent were part of Architecture Engineering as shown in Table 2.

The demographics are also shown in the form of a pie chart as shown in Fig. 5.

These respondents were holding junior, mid-career and senior-level positions. 31 % of the respondents are Project managers, 12 % are University professors and Site engineers (26 %), Resident engineers (18 %) and senior architects (13 %) as shown in Fig. 6.

Table 3 shows the questions that were asked in the questionnaire for the participants to respond using a Linkert scale. Individual emails were sent to the professionals inviting them to participate in the survey. The first reminders were sent after a week. It took four months to receive responses from the participants. The questionnaire used for this study included a total of 20 questions asking professionals to respond to these questions using the 1 to 9 Linkert scale. All the questions were divided into two categories of sustainability and resilience impacting the cost of Green Resilient Building. The responses were collected analysed and processed to obtain relevant information. The questions are designed in a way that the respondents can evaluate the impact of each factor on the cost of Green Resilient Buildings which were the scope of this paper as they not only helped enhance the sustainability of the communities but also increased their resilience in the face of natural disaster.

3.3. Performing analysis of variance

Statistical analysis was done using analysis of variance (ANOVA). The p-value <0.05 shows the data's high precision, which can be used with 95 % confidence level. ANOVA is a statical technique which is used to compare the difference between the means of various groups, helping the users to understand if the difference is mainly due to different treatments or simple random chances.

3.4. Checking the density of the data

The density of the data enables a deep understanding of the users for analysis and decision-making; helping to visualize the point where the data is concentrated allowing for more informed, effective and tactical decisions.

3.5. Checking the probability of the data

The density of the data enables a deep understanding of the users for analysis and decision-making; helping to visualize the point where the data is concentrated allowing for more informed, effective and tactical decisions.

3.6. Calculating relative importance index

The data collected based on factors of sustainability and resilience, were analysed using the relative importance index (RII). The analysis consisted of bar charts ranking various factors of sustainability and resilience based on their RII. The areas of green resilient buildings that have been focused in this study range from 112.5 ft^2–675 ft^2. The analysis shows the factors and main factors of the highest contribution to the green resilient buildings in the developing world. The calculation of the RII was based on the following

Table 2
Target population sample of the respondents.

Category	Property	Percentage
Profession	Civil Engineering	31
	Mechanical Engineering	26
	HVAC Engineering	18
	University Teaching	12
	Architecture Engineering	13
Designation	Project Manager	31
	Site Engineer	26
	Resident Engineer	18
	Senior Architect	13
	Professor	12

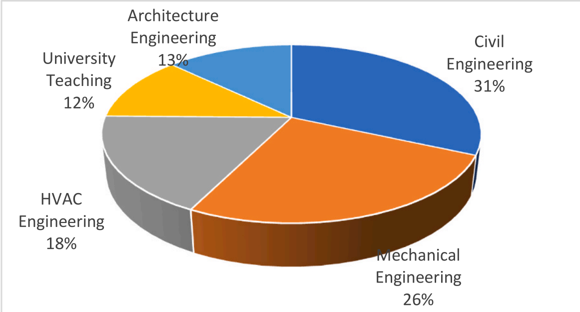

Fig. 5. Demographics of respondents.

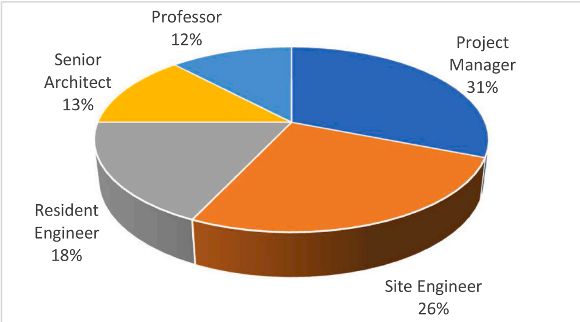

Fig. 6. Designations of respondents.

Table 3
Questions asked in the survey to investigate the impact of factors on Green Resilient Building.

Sr #	Questions	Main factors	Linkert Scale								
			1	2	3	4	5	6	7	8	9
1	How much lack of awareness contribute to cost of Green Resilient Building?	Sustainability									
2	How much do design complexities contribute to the cost of Green Resilient Buildings?										
3	How much do cost of operations contribute to the cost of Green Resilient Buildings?										
4	How much does unskilled labour contribute to the cost of Green Resilient Buildings?										
5	How much does small or no tax relief contribute to the cost of Green Resilient Buildings?										
6	How much do fewer options for materials contribute to the cost of Green Resilient Buildings?										
7	How much do sophisticated installations contribute to the cost of Green Resilient Buildings?										
8	How much do inadequate supplies contribute to the cost of Green Resilient Buildings?										
9	How much does the drainage facility contribute to the cost of Green Resilient Buildings?	Resilience									
10	How much does the solid roof contribute to the cost of Green Resilient Buildings?										
11	How much does the number of storeys contribute to the cost of Green Resilient Buildings?										
12	How much does the emergency power contribute to the cost of Green Resilient Buildings?										
13	How much does the emergency lights contribute to the cost of Green Resilient Buildings?										
14	How much does the food storage contribute to the cost of Green Resilient Buildings?										
15	How much does the safe shelter in disaster contribute to the cost of Green Resilient Buildings?										
16	How much does easy road access contribute to the cost of Green Resilient Buildings?										
17	How much does a safe place for livestock contribute to the cost of Green Resilient Buildings?										
18	How much does location on a waterway contribute to the cost of Green Resilient Buildings?										
19	How much do nearby communities contribute to the cost of Green Resilient Buildings?										
20	How much does clean environment contribute to the cost of Green Resilient Buildings?										

formula as shown in Equation (1).

$$RII = \frac{\sum W}{A^*N} 0 \leq RII \leq 1 \quad (1)$$

Where;

W is the weight given to each factor by the respondents (ranging from 1 to 9),

A is the highest weight (i.e. 9 in this case), and.

N is the total number of respondents (250 in this research case).

The values of RII range from 0 to 1 with 0 not exclusive [77]. 0.8≤RII≤1, 0.5≤RII≤0.8, 0≤RII≤0.5 are considered to be high, medium and low in this study of green resilient buildings. Researchers have used RII to give weightage to different factors [78]. A total of twenty factors are selected for this study which include inadequate awareness, complex designs, operational cost, lack of expertise, no/small tax relief, lack of green building material, high skill needed to use the material, inadequate supplies, scarcity of materials, lesser options of materials, lesser aesthetic appeal, higher cost of materials, longer design time, lack of political will, difficulty in planning, higher monitoring standards, execution of the project and size of the site. These factors are assessed for their relative importance index (RII).

3.7. Calculating Analytic Hierarchy Process (AHP) analysis of sustainability and resilience

[79] proposed the Analytic Hierarchy Process (AHP) which is now commonly and preferably applied for multi-criteria decision-making to find solutions of problems involving prioritizing criteria [80]. This has helped several researchers and scientists to make judgements according to various criteria while minimising inconsistencies [81]. The AHP focuses on paired comparisons [82] while transforming a multi-dimensional scaling problem into an uni-dimensional scale [82].

Due to its immense flexibility; AHP has been used extensively for the last 20 years [83]. [84] reviewed several AHP-based papers and claimed that AHP is versatile and can be used effectively as a standalone tool or in coordination with other tools to solve decision-making problems. This study has used AHP to overcome the difficulty of deciding the comparative weights of each factor in the decision-making process [85] as shown in Fig. 7.

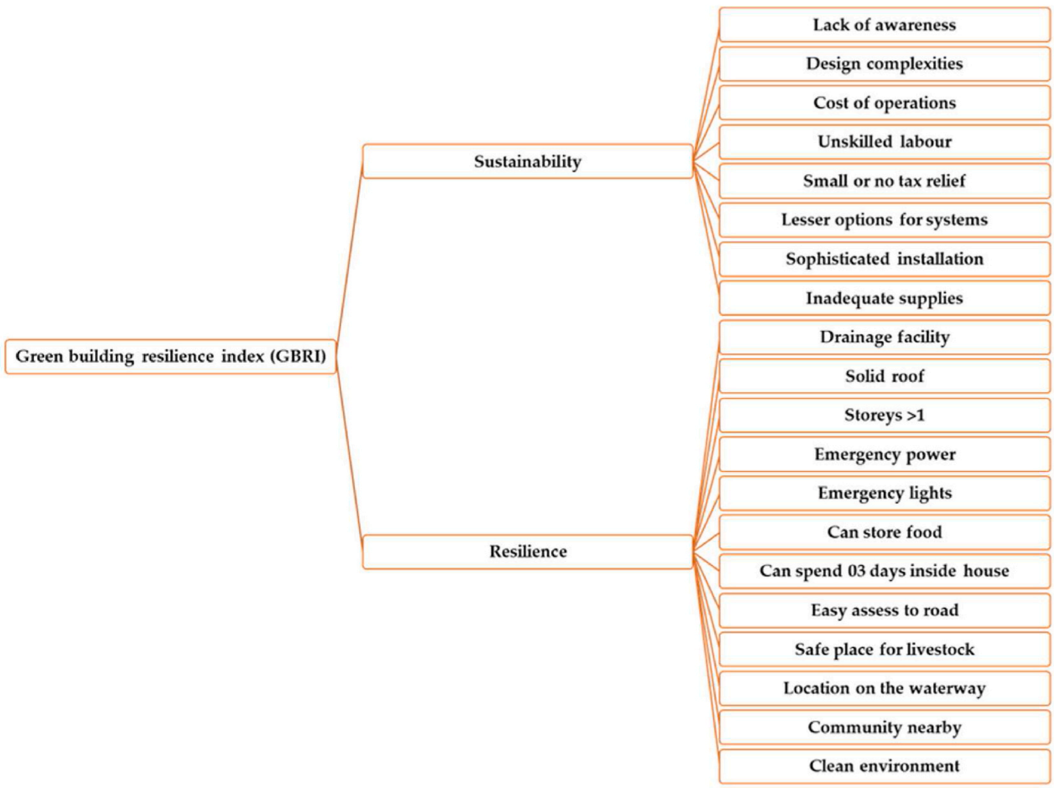

Fig. 7. Analytic Hierarchy Process (AHP) analysis of sustainability and resilience.

4. Results and discussion

The bar chart in Fig. 8 shows the comparison of RII of factors affecting the sustainability of the building. Design complexities in green sustainable buildings have an RII>0.8 i.e. having a high (H) impact on the cost of building sustainability. Similarly, factors like the lack of awareness, cost of operations, unskilled labour, small or no tax relief and sophisticated installations have 0.8>RII >0.5 ie. Having medium impact (M) on the cost of sustainability. Lesser options of the system and inadequate supplies have 0<RII<0.5 making them factors having a low impact (L) on the cost of sustainability of the building.

Fig. 9 shows the comparison of RII of sub factors affecting the resilience of the building. Solid roof of the housings, storey>1, emergency power, emergency lights, food storage, 3 days inside stay, easy assess to the road, location of the waterways, nearby community and clean environment all have RII>0.5 which means they have a medium (M) impact on the resileince of the building. Safe place for the live stock and drainage facilites have lesser (L) impact on the resilience of the green buildings (RII< 0.5).

RII related to the sustainability and resileince are shown in composite manner for assessment of weightage for green resilient building index as shown in Fig. 10.

Presented in Fig. 11 is the histogram of the RII, showing the density of RII values and presenting how the RII values are spread across the whole range of data and how many same RII values are repeated for all subfactors. The fitting lines for the density show that large areas of the buildings have higher peaks of the density ranging from 0.1 to 0.4 which means that the most of the RII values are lying in a narrow range making the density very high. The buildings with less covered area show a very wide range of density with peaks from 0.4 to 0.6 RII with lower peak i.e., 2.

The cumulative probability of the RII in Fig. 12 shows the peak probability at an RII value of 0.4 with large covered areas. Whereas the probability for the less covered area buildings reaches the peak value of 1 at the RII ranging from 0.8 to 1. This aspect demonstrates that the peak probability of small buildings is achieved at lower RII and vice-versa. Hence, most of the data falls between 0.3 and 0.5.

250 respondents were asked to answer 20 queries about 7 building sizes. From the 250 responses, data for each building size was extracted only from those responses in which all 20 queries about that building size were answered. Also, in order to maintain independence of building size groups in one-way ANOVA, it was assured that data of only one building size were extracted from each response to be processed in ANOVA. Table 4 shows degrees of freedom for ANOVA of the RII of questions/factors. The degrees of freedom are the same for the RII of all queries. On the other hand, $p < 0.05$ indicates that building size significantly impacts the RII of the other queries as shown in Table 5.

Fig. 13 provides a flowchart diagram and a detailed explanation of the operational algorithm for the GRBI evaluation model to assist in clearer communication of the authors' proposed approach towards finding the cost of Green Resilient Buildings.

The values of the factors on the Linkert scale obtained from the questionnaire are converted into the Relative Importance Index (RII) for the factors impacting sustainability and resilience. Afterwards, for every individual covered area (112.5 ft^2,169 ft^2, 225 ft^2, 338 ft^2, 450 ft^2, 563 ft^2, 675 ft^2) the mean of RII is calculated to get values of sustainability and resilience for a covered area. The weightage average is then taken to find the Green Building Resilience Index (GBRI). For instance, for a covered area of 112.5 ft^2, the sustainability factors have individual RII as 0.6, 0.85, 0.65, 0.64, 0.52, 0.17, 0.22, 0.3 giving a mean value of sustainability as 0.49. Similarly, RII individual values of resilience factors for 112.5 ft^2 are 0.31, 0.55, 0.27, 0.6, 0.7, 0.62, 0.29, 0.62, 0.4, 0.5, 0.27, 0.6 giving

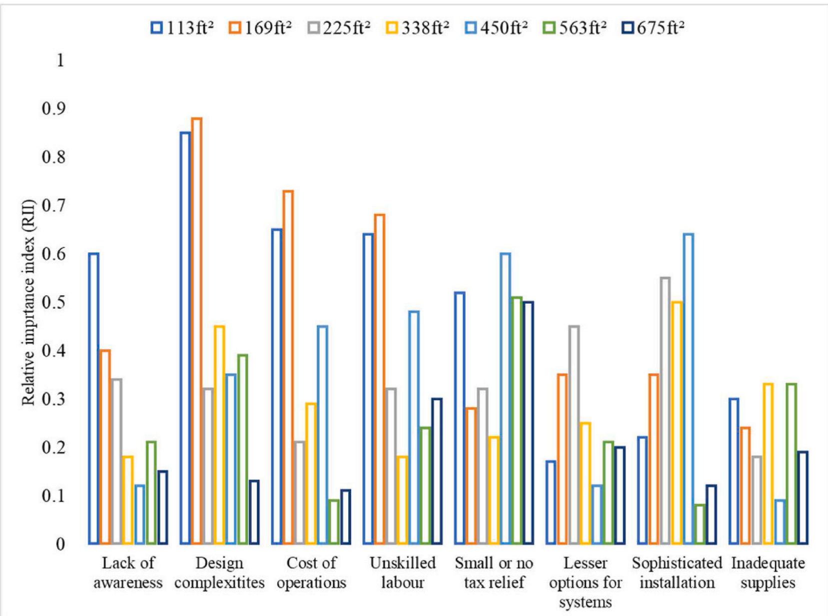

Fig. 8. RII of the subfactors on the sustainability of the building.

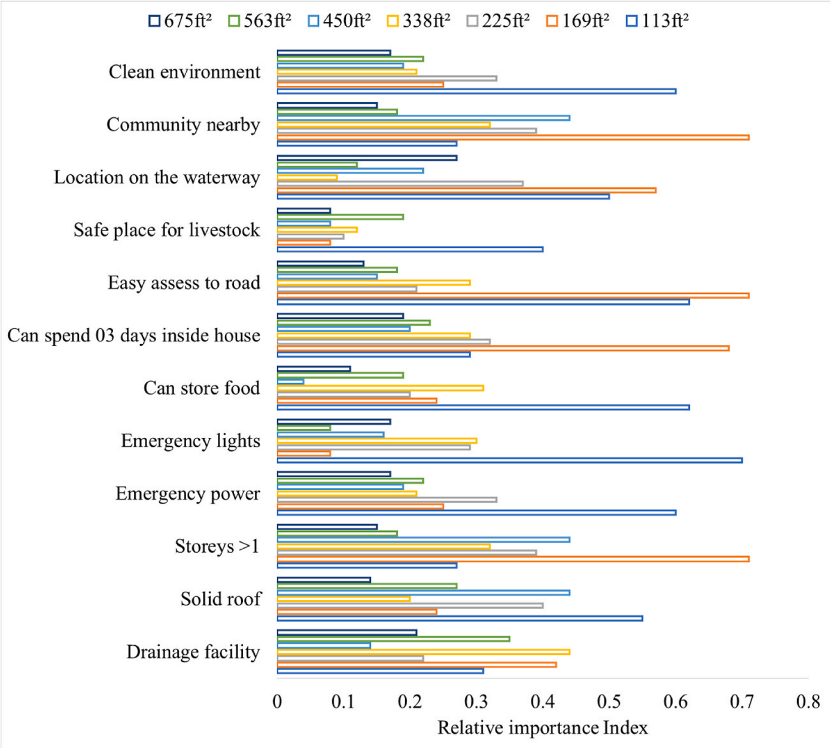

Fig. 9. RII of the factors for the resilience of the buildings.

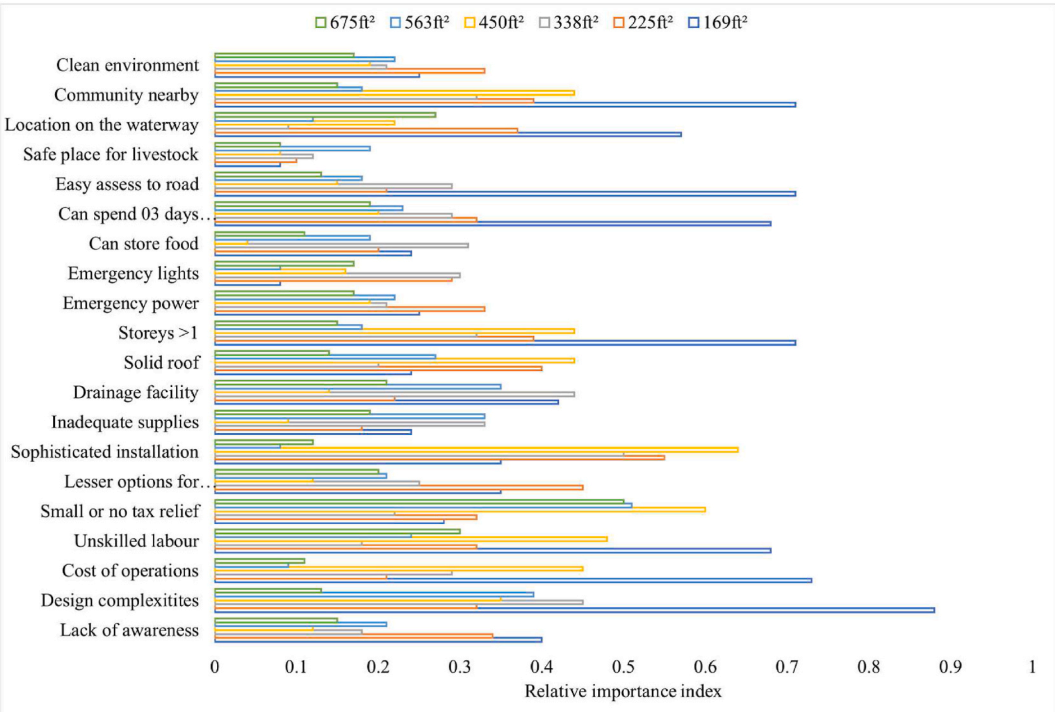

Fig. 10. RII of the factors on green resilient building.

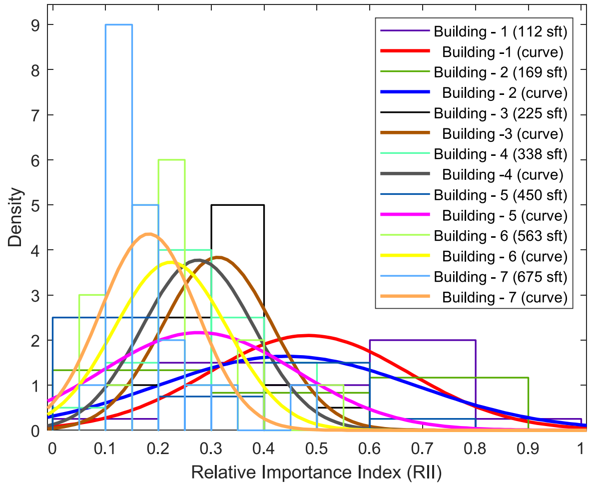

Fig. 11. RII and density of the factors on green resilient building.

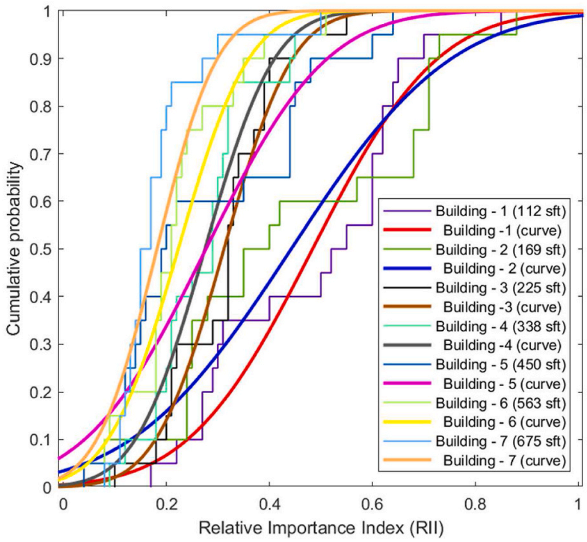

Fig. 12. Cumulative probability of factors on green resilient buildings.

a mean value of 0.41. The Green Resilient Building Index (GBRI) is the weightage average of sustainability and resilience - 0.45. These steps are repeated for all the different covered areas and a model is developed using MATLAB as shown in Equation (2) below.

Green Resilient Building Index (GRBI) =

0.0037 + 0.5275 (Sustainability) + 0.4685 (Resilience) (2)

where the goodness of fit shows $R^2 = 0.9868$, SSE = 0.00013, adjusted $R^2 = 0.9716$. The model indicates that low values of resilience and sustainability yield lower values of GRBI and as these values increase GBRI also increases.

To find the green resilient building index (GRBI) based on the relative importance index (RII) of resilience and sustainability factors a model is developed as shown in Fig. 14.

Furthermore, to predict the cost of green resilient buildings a market survey to estimate the cost of construction of conventional buildings based on materials and construction activities rates was done as shown in Fig. 15. Item rates as of 2024 were used for this data.

The conventional item rates of all the significant construction materials and the area of the buildings built in the housing units were correlated for the prediction of the cost of green resilient buildings based on the data presented in Fig. 16.

The following equation is the predictive model for the cost of green resilient buildings based on GRBI and the cost of a similar conventional structure as shown in Fig. 17 and presented in Eq (3).

The evaluation of green resilient building cost, the curve fitter techniquue in MATLAB was used to develop an equation as following:

Table 4
Analysis of Variance Results for individual questions/factors.

Query	F	p
Lack of awareness	7.57342334	6.837E-05
Design complexitites	6.8725963	0.000145827
Cost of operations	25.1975893	4.53192E-10
Unskilled labour	5.04329023	0.001283814
Small or no tax relief	5.18623475	0.001070956
Lesser options for systems	2.91925437	0.024386916
Sophisticated installation	10.6251321	3.73235E-06
Inadequate supplies	1.42378129	0.0240704891
Drainage facility	1.34182357	0.0272144429
Solid roof	1.40414007	0.0247921522
Storeys >1	3.66518431	0.008216553
Emergency power	2.9894617	0.021961944
Emergency lights	1.23948563	0.031654399
Can store food	3.97660872	0.005307273
Can spend 03 days inside house	3.38787403	0.012231192
Easy assess to road	3.28888818	0.014124798
Safe place for livestock	1.88746315	0.0118266346
Location on the waterway	2.44415531	0.050084655
Community nearby	1.27996415	0.0298272663
Clean environment	3.43095882	0.011492002

Table 5
Analysis of variance results.

Source	Sum Sq.	d.f.	Mean Sq.	F	p
Building size	0.652274	6	0.108712	3.430959	0.011492
Error	0.8872	28	0.031686		
Total	1.539474	34			

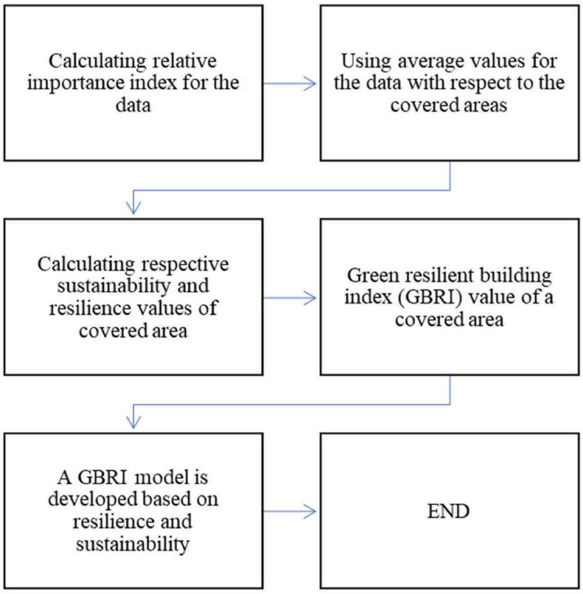

Fig. 13. Flowchart diagram for a detailed explanation of the operational algorithm for the GRBI evaluation model.

$$\text{Green Resilient Building Cost (USD)} = 3969 + 1.043\ (\text{Conventional Cost USD}) - 6318\ (\text{GRBI}) \quad (3)$$

where the goodness of fit shows $R^2 = 0.932$, SSE = 3.6470e+06, adjusted $R^2 = 0.9916$. The model indicates that low values of resilience and sustainability yield lower values of GRBI and as these values increase GRBI also increases as shown in Fig. 17.

Past researches show that the green building cost is higher than the conventional; however, this study presents an analysis and model for the prediction of the composite impact of “sustainability” and “resilience”. Moreover, the cost related to this composite

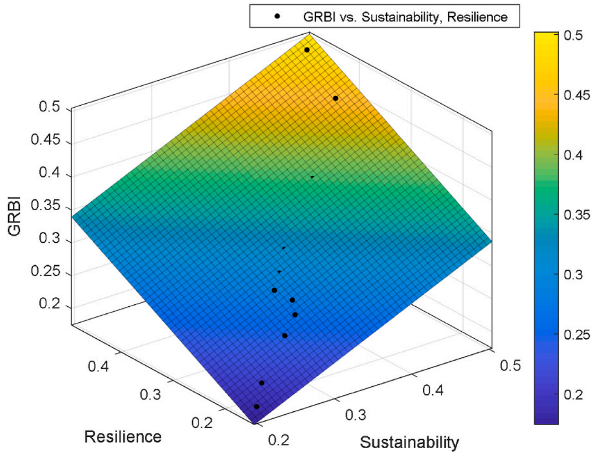

Fig. 14. Green resilient building index (GRBI) versus resilience and sustainability.

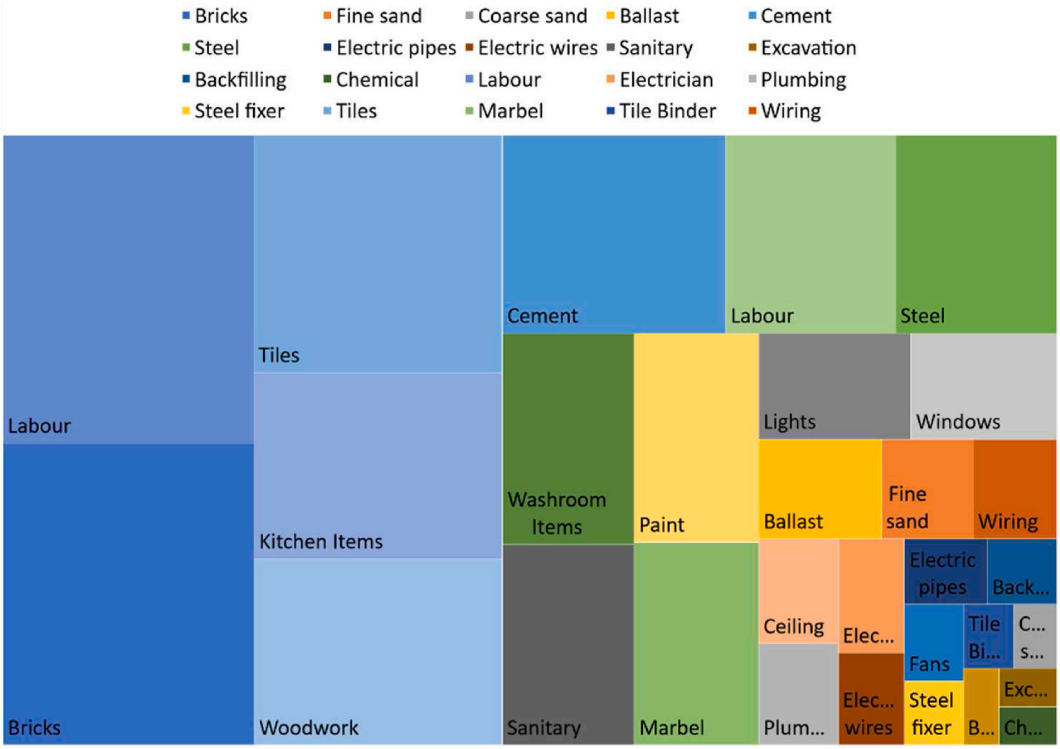

Fig. 15. Item rates for the construction of conventional building.

behaviour can also be predicted by the proposed model in this research. These models are user-friendly and can be directly implemented in the construction market for onsite decisions by developers and policymakers. These models can contribute to the mitigation of CO_2 emissions globally to save future generations.

5. Validation

Data on the cost of the green resilient buildings was collected from the field for the validation of the model and the values were compared with the predicted ones. The predicted and actual values of green resilient buildings fall within 10 % of the line of equality (1:1 line) showing the significance and confidence for the use of these models in the construction market as shown in Fig. 18.

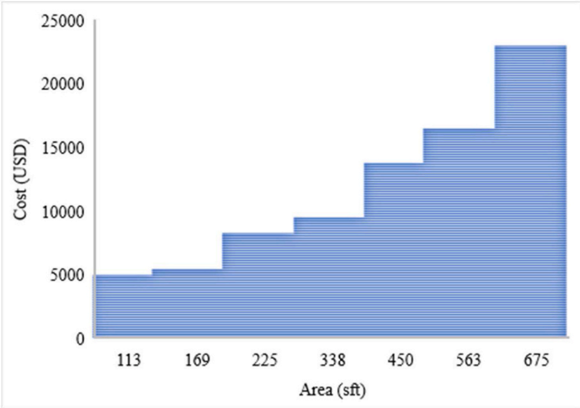

Fig. 16. Cost of conventional buildings versus area of the buildings.

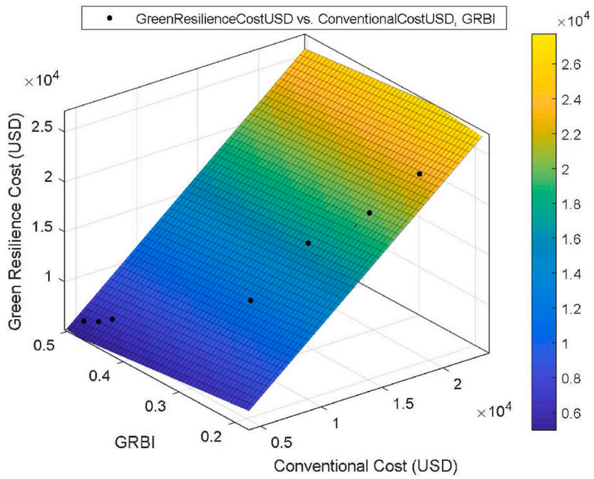

Fig. 17. Cost of green resilient building based on GRBI and conventional building cost.

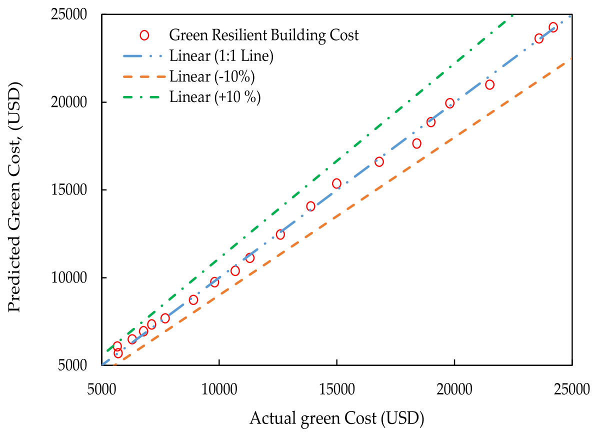

Fig. 18. Validation of the economic impact model.

6. Limitations

These models calculate the upfront cost of green resilient buildings and do not include the life cycle savings that will result from the sustainable and resilient behaviour of these structures. Hence a model which includes the cost savings due to energy efficiency, lesser waste production, use of natural light and durability and safety due to resilience will have a more accurate prediction about the cost impact of these buildings.

7. Conclusions

In this study, the factors affecting the cost of green resilient buildings are discussed in detail by the method of relative importance impact (RII). The models for the prediction of the green resilient building index (GRBI) and cost of green resilient buildings are developed for implementation in the construction industry. Nevertheless, these models provide a better understanding of the cost impact of the green resilient buildings based on their GRBI – a concept rarely discussed by the past researchers. The following conclusions have been drawn from the analysis and results of this research.

- An innovative model for the assessment of the Green Resilient Building Index (GRBI) has been proposed. This model can be used for evaluation of the effect of sustainability and resilience as individual factors, on the composite output i.e., GRBI for use in the construction of green resilient buildings. The equation illustrates that sustainability has a higher impact on GBRI than resilience.
- Another model calculates the cost of a Green Resilient Building based on GRBI and the conventional cost of the building; hence considering the composite effects of sustainability and resilience in the building.
- The green resilient cost model has been validated by the on-ground constructed buildings which show that the predicted and actual construction cost fall within 10 % of the 1:1 line. The analysis of variance (ANOVA) for the research data shows a 95 % confidence level for direct use by practitioners in the construction industry.

CRediT authorship contribution statement

Muhammad Ali: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ayesha Zubair:** Conceptualization. **Jahanzaib Israr:** Writing – review & editing. **Wasim Abbass:** Writing – review & editing. **Zubair Masoud:** Writing – review & editing. **Abdullah Mohamed:** Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40825.

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