Developing and Applying a Model for Evaluating Risks Affecting Greening Existing Buildings

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Abstract: Improving building performance through reducing negative environmental impacts can be achieved by greening existing buildings (GEB), which is considered a very important sustainability process. Due to the risky and uncertain nature of the process of GEB, a growing amount of attention should be given to eliminating the effects of risks on GEB. This research aims to identify most expected risk factors related to GEB, as well as to evaluate their effects through calculating risk factor characteristics, such as risk factor presence (RFP), impact on the GEB process (IGEB), and impact on building performance in the long run (IBP), as new indices describe these risks. Sixty-six risk factors were categorized in seven risk groups related to the economic aspect, social aspect, environmental aspect, managerial aspect, sustainability operation, sustainable design, and renovation. Moreover, a fuzzy model for risk analysis was developed to combine the multi-effects of the aforementioned three risk factor characteristics in one index representing the risk factors’ overall importance. The model was applied and verified for data collected in Saudi Arabia. The results of this study showed that the most important risk group is the greening process of environmental control, while the least important is the greening process of renovation and construction. Using the proposed model improved the results of evaluating risks affecting GEB through merging the multi-effects of risk factor characteristics. The results and analysis proved that the most important key risk factors were environmental in nature. An intricate relationship of the impacts on the GEB process and building performance with the overall importance of the risk factors was clearly found. The decision makers who deal with greening projects in Saudi Arabia should be aware of the key risks identified in this study. The proposed methodology and model can be easily applied to other countries to help decision makers in evaluating their GEB projects, as well as comparing more greening projects based on risk analysis.

Keywords: green building; risk analysis; fuzzy; sustainability

1. Introduction

Over the last two decades, the importance of the green building concept has been increasing significantly [1]. A project’s risk is generally defined as an uncertain event that, if it does happen, has a positive effect (opportunity) or a negative impact (threat) on at least one objective of the project [2,3]. Threats of risks considerably affect any project’s objectives,
such as cost, time, quality, life cycle performance, and the project’s scope [4–6]. Limited
research efforts were found concerning risk analysis in green building projects. Most
of them were concerned with identifying the challenges faced when applying greening
concepts to newly constructed buildings rather than existing ones [7,8]. No previous in-
depth work has studied the risk interdependencies in green building projects considering
both the project’s life cycle and multiple project risks or even their impact on the project’s
planned objectives. More research is needed on the economic feasibility of GEBs, including
cost/benefit analysis from the perspectives of major market participants, as well as on the
building life cycle.

Recently, the GEB approach has been given considerable attention within the construc-
tion industry in order to catch up in the race towards sustainable green practice and its
numerous benefits [9,10]. The process of GEB faces many risk impacts, either during the
construction stage or in long-term building performance. These risks should be accurately
identified. The GEB risk factor identification process is a part of the research methodology
to bridge this gap in the knowledge. The proposed factors were mainly identified through
a literature review, which are widely explained hereinafter, and through field survey.

Several evaluation models dealing with risks have been developed by many research
works [11–14], while no previous study has handled the combined effect of risks on multi-
objectives in the GEB process. Based on that, a mathematical model is needed to analyze
the identified risks and evaluate the effect of risks on certain objectives. In cases where
there are many objectives of a project, such as execution process and performance, it is
necessary to combine these multi-objectives. In this research, a risk analysis model based
on the fuzzy logic technique is proposed to evaluate and quantify risk factors affecting
GEB by combining three characteristics of such risks in one index. The first characteristic
is the presence of risks, which represents the likelihood of risks in the investigated case
study. The other two characteristics are the risk impacts on the greening process during
refurbishment and their impact on the building performance in the long run. The latter
two are considered the most important objectives in GEB projects.

Risks are best represented using qualitative and linguistic variables that cannot be
analyzed or numerically quantified [15]. Many tools to quantify these linguistic variables
are being used for research purposes [16]. In this research, a fuzzy logic tool is used to
quantify the risks’ linguistic variables. Fuzzy logic was chosen for its known capability
to handle imprecise non-statistical datasets [17], in addition to processing uncertainties
of linguistic variables that represent their likelihood and severity [11], such as in the case
of risk.

Identifying these risk factors and developing such a model are the main contributions
of this research. In addition, the proposed model is considered a very important tool for
supporting decision makers within the GEB industry.

2. Study Objectives

The main objectives of this study can be summarized as follows:

(1) To identify the extent of the risk factors affecting GEB, as well as categorizing them in
appropriate risk groups.

(2) To evaluate the risk factor presence (RFP), besides the effects of these factors on GEB,
through calculating their impact on GEB (IGEB) and impact on building performance
in the long run (IBP).

(3) To design and develop a risk analysis model using the fuzzy logic technique to help
calculate the combined effect of a risk presence and its effects on both GEB and IBP.
The proposed model can support decision makers who deal with the GEB process to
support their actions.

(4) To apply and verify the risk model using the collected data on existing buildings in
Saudi Arabia as a case study. Moreover, the research aims to present an in-depth
discussion of the model’s results and highlights the critical risk factors. The data
include RFP and the effects on GEB and building performance in the long run. In
addition, the research identifies the importance of key risks based on combining RFP, IGEB, and IBP. The proposed model can be adopted to satisfy other similar situations in Saudi Arabia and other countries.

3. Research Methodology

The research methodology includes ranking and assessing the identified risk factors due to their importance using the proposed risk model, which depends on combining the RFP, IGEB, and IBP based on many logical rules. The methodology relies on field surveys, principally semi-structured interviews, and brainstorming sessions. The methodology contains three main steps, as explained in order in the following sections. Figure 1 illustrates the research methodology overview.

Figure 1. The research methodology overview.
3.1. Identifying Risk Factors Affecting GEB

Based on the literature review concerning risks and barriers related to green buildings and GEB, many risk factors were identified. The semi-structured interviews were selected to be conducted at this stage as it would provide respondents the opportunity to express their suggestions regarding modifications they may make in order to improve the survey and its results [6]. The main objectives of this stage are confirming the risk factors affecting GEB by modifying the preliminary list through adding and merging or removing some of the risks to designate the present situation in GEB. Classifying the risks was also conducted according to suitable risk groups. The output of this stage is a final list of risks affecting GEB under seven groups to be used in the last step of the methodology.

3.2. Developing the Proposed Risk Analysis Model (RAMGEB)

The second step of the methodology is the proposal and development of the risk analysis model for all previously identified risk factors. Many techniques, methods, and models can be introduced to measure and evaluate the effects of risks on project objectives. A risk analysis model to contribute risk perception to green building projects for industry practitioners was proposed to calculate the importance of constraints and risk factors associated with the objectives of such projects. The model includes 6 constraint factors, 22 risk factors, and 11 objectives throughout the green building project life cycle [14]. The motivation factors against risks in green building project development in Malaysia were qualitatively studied to highlight the importance of economic issues [18]. A model was presented for the interactive networks of the risks associated with different stakeholders in green building projects to gain an understanding of the key risk networks [19].

A quantitative model to predict the impact of greening on building energy consumption was developed using NASA satellite data. The model aimed to establish the land characteristic indices, including land surface temperature, normalized differential vegetation, building profile, water-resistant surfaces, and modified normalized difference water [10]. A study was introduced using failure mode and effects analysis to investigate the obstacles to GEB using Leadership in Energy and Environmental Design for Building Operations and Maintenance. The intricate relationship between technical, financial, organizational, social, and environmental factors was determined [20]. A set of green maintainability indicators for building projects with highly desirable levels of green maintainability was validated using a framework for the purpose of overcoming the barriers of green buildings from five levels [21]. Finally, a new criterion named “greenship” was developed for evaluating green buildings, depending on aspects of energy efficiency and conservation. The greenship model concerned energy consumption savings in high-rise office buildings by calculating the energy efficiency index and then classified the cases into intensive, standard, and efficient groups [22].

The proposed risk analysis model for GEB (RAMGEB) was developed to handle and combine the three identified parameters of risks affecting GEB for the purpose of evaluating the overall effect of risk factors on GEB via a satisfactory and easy technique. The proposed model can be used in wide range and can be applied to other risks affecting GEB.

Fuzzy logic can address indefinite datasets, including data featuring non-statistical uncertainties. In addition, the main benefit of fuzzy set theory compared to other methods is its capability to work with linguistics [23]. For these reasons, fuzzy sets can be used to qualify the linguistic variables that represent the characteristics of a certain project [24]. Many recent studies have applied fuzzy logic theory in evaluating data in construction projects. For example, fuzzy reasoning techniques introduce a systematic tool to address quantitative data in the construction process [25]. Fuzzy logic was used in supporting a decision for evaluating and selecting a construction project amongst many available projects [26]. Fuzzy logic is utilized to manage the risks of construction projects in an uncertain situation through a three-stage approach [27].

In this study, the RAMGEB can be established via three steps, specifically, constructing the fuzzy membership function, identifying the fuzzy rule base, and defining the fuzzy
The logical rules in the proposed model can be constructed based on the assumption of relating the three input parameters (RFP, IGEB, and IBP) to each risk factor. Furthermore, the model output represents the importance of a risk factor as a result of the combined effect of the three inputs. This suggestion was characterized by the authors and validated by the experts in the brainstorming session. An example of the proposed three-premise rule is as follows:

If risk factor presence is high, impact on GEB is medium, and impact on building performance in the long run is low, then risk factor importance is acceptable.

After determining the logical rules, one should select the membership function, which represents the fuzziness degree of linguistic variables by representing a numerical meaning for each linguistic variable’s proposed labels [15]. The membership functions classify the range of input or output values that correspond to each label. The membership function of each label does not describe boundaries when the label is fully applied to one side of a cutoff and not at all to its other side.

According to many studies on applied construction and risk management, the triangle shape is the most suitable in cases similar to that of the current investigation [28]. The form of the proposed triangle membership function has been used in many risk assessment fuzzy models and has been selected on the basis of previous research [11]. Many agreement tests to prove that the triangle shape is the most suitable in cases similar to that of the current study have been conducted [15]. The triangular shape is proposed as a membership function in the proposed model for all input and output sources, as shown in Figure 2.
Many researchers identified and summarized challenges, key factors, or barriers affecting green buildings and sustainability in many ways and in different arrangements of risk factors. For example, many challenges that faced green buildings’ construction project managers were identified to determine the required critical knowledge areas and skills that are necessary to respond to such challenges [30]. Many field surveys were conducted with project managers to improve their knowledge base and competences related to effectively executing sustainable projects [31]. Additionally, risks in green commercial buildings were presented to compare risk criticalities with those in traditional counterparts and to propose mitigation methods that can tackle these risk factors [8]. The top key risks in green commercial buildings included “inflation, currency and interest rate volatility worsened by the import of green materials, durability of green materials, damages caused by human error, and shortage of green materials”. Green building paradigms have been identified, including critical success factors, barriers, drivers, risks, and benefits. A framework was developed to explain the role of various paradigms in sustainability progression [32]. The risks affecting the main requirements of green buildings under four sustainability groups (economic, social, environmental, and management) were also briefed [33]. The key drivers of green building were investigated to determine whether or not these drivers have changed over time [34]. The key drivers of green building included many factors that are not expected to significantly change over time, such as “rising energy costs, the industry’s Green Star rating system, competitive advantages and legislation”. Other risks, such as “political, social, certification risks, financial, technological and managerial risks”, were studied and arranged based on probability of occurrence and degree of influence [5].

The difficulties preventing green buildings’ certification in operational stages were identified [35]. The green public procurement criteria proposed for office buildings and val-
idated against sustainability indicators included in three building sustainability assessment tools were introduced [36]. A life cycle cost analysis of non-residential green buildings was determined [37].

In terms of environmental impact, many factors affecting the development of low-carbon buildings were concluded. Of those, three factors were found to be prioritized over other factors towards the aim of low-carbon willingness. They were, in order, using the structural equation modeling technique, critical factors that significantly affect low-carbon construction, and return on investment [38]. The actual environmental performance of existing residential buildings after greening was investigated within cold and severely cold climatic regions. The results of this study showed that the effect of greening existing buildings, under investigation, is not obvious and needs further enhancement. The reasons behind that poor greening performance were further discussed, and greening program guidelines were developed for GEB within such climates [39].

The opportunities or success factors in construction projects can be enhanced as positive risks [40]. Moreover, researchers may use risk factors in maximizing profits in green buildings as success factors. The success of the GEB process depends on many factors, such as occupants’ behavior, GEB methods of applications, government’s support, property owners’ intent, and building design criteria [41]. A green audit award is suggested to help in identifying the green deficiencies of the existing buildings aiming to support a successful green improvement plan based on feasibility and cost effectiveness [42]. Many critical success factors were investigated and established for the delivery of sustainable public housing estates, such as the project managers’ performance; the owner organization; the team members’ characteristics; and the project’s environmental context [43]. Other success factors were recognized to limit constructability issues in terms of net-zero energy home sustainability [44]. On the other hand, critical success factors and opportunities for projects regarding sustainable buildings and green infrastructures were considered in various groups [45,46].

There is a need to identify risks affecting green sites during the planning stage, because they can represent a key issue for site sustainability in green building development. Many risks were identified, such as water pollution reduction [47], green parking, thermal environment, use of land resources [48], car use, land diversity, non-residential land use, and employment influence on the distance to facilities [49].

One of the important issues in evaluating greening existing buildings is their acceptability for using new technologies in order to save energy and the utilization of renewable energies for the purpose of minimizing negative effects on the environment. Energy consumption of aged buildings increases year by year, and, as such, greening is essential [50]. A new method was developed based on the use of failure mode and effects analysis to evaluate the risks to GEB using leadership in energy and environmental issues. The results showed that over half of the identified reasons for failure were technical in nature, with financial and organizational causes. The analysis also showed the intricate relationship between technical, financial, organizational, social, and environmental factors [20].

A risk factor may have one or more sources and one or more effects. GEB faces many critical risk factors that affect the objectives of such projects [48,51–53]. Based on the literature review outlined above that regards risks and barriers related to sustainability and green buildings, many risk factors were investigated and classified into risk groups. It was decided to conduct the semi-structured interviews during this stage. After filtering the preliminary list of risk factors and risk groups that were collected from reviews, the output of this stage was determined to be a final list of risks, including 66 risk factors affecting GEB distributed in seven groups. The results of this stage are summarized in Table 3. As presented in this table, the risk groups are as follows: greening process of economic risks, greening process of social risks, greening process of environmental control risks, greening process of managerial risks, green building and sustainability operation, greening process of design-related risks, and greening process of renovation and construction stage risks. Further clarification is provided in the section regarding risk group analysis.
| No. | 1. Greening Process Economical Risks (G01)                                                                 |
|-----|-----------------------------------------------------------------------------------------------------------|
| RF01| High overall cost and budget of GEB including materials, products, and technology                        |
| RF02| Lack of governmental fund supporting GEB approach                                                         |
| RF03| Weak green building market demand for GEB                                                                |
| RF04| Lack of accurate estimation of green building long-term economical benefits and investment return cycle   |
| RF05| Negative effect of inflation on GEB                                                                     |
| RF06| High cost of conducting a green building standard assessment                                             |
| RF07| Lack of sufficient funding for human resources, GB officials and technical staff in local authorities     |
| RF08| Lack of GB project motivation and incentives for owners and investors                                    |
| RF09| Unclear roles of owner’s financial involvement or commitments                                          |

| No. | 2. Greening Process Social Risks (G02)                                                                  |
|-----|---------------------------------------------------------------------------------------------------------|
| RF10| Low community satisfaction with and interest in GB features                                           |
| RF11| Negative impact of GB on society                                                                      |
| RF12| Lack of end user’s awareness and familiarity with sustainability in general and GB technical features use in specific |
| RF13| Lack of owners’ awareness and ability to define GB scope as well as future benefits                    |
| RF14| Unacceptability of GB approach due to cultural difference                                             |
| RF15| Lack of interest and commitment to GB systems amongst greening project team members                   |

| No. | 3. Greening Process Environmental Control Risks (G03)                                                   |
|-----|---------------------------------------------------------------------------------------------------------|
| RF16| Low response of GB to local geography and climatic conditions due to insufficient on-site environmental investigations |
| RF17| Unstable environmental measures performance of GB through time                                         |
| RF18| Negative impact of GB end users’ behavior on greening process stability                                |
| RF19| Poor expected energy efficiency in GB during operation time                                             |
| RF20| Lack of use renewable energy resources and low energy consumption equipment                            |
| RF21| Lack of environmentally friendly alternative transportation within GB context                          |
| RF22| Inability of greening process to preserve existing natural environment within GB site                  |
| RF23| Low performance of water resource systems and rainwater control system                                  |
| RF24| Lack of existing designed solid waste and unclean water treatment and control system                   |
| RF25| Lack of GB context environmental information                                                           |
| RF26| Dysfunction of internal air quality control scheme                                                     |
| RF27| Inefficiently used thermal comfort measures and strategies in GB thermal treatment                     |
| RF28| Unsuitable used natural and artificial lighting systems within GB                                       |
| RF29| Inability of GB to achieve acceptable level of acoustics and noise control                            |
| RF30| Inability of GB to achieve acceptable level in environmental assessment and rating process            |

| No. | 4. Greening Process Managerial Risks (G04)                                                            |
|-----|---------------------------------------------------------------------------------------------------------|
| RF31| Lack of clear GB and sustainability objectives in greening process and agenda                           |
| RF32| Lack of expertise and experienced team and firms in GB technology and sustainability issues             |
| RF33| Lack of sufficient powers and government strategical support to enforce sustainable options as regulations |
| RF34| Lack of qualified greening professionals along with weak investment in human resources’ skills development |
| RF35| Lack of communication and collaboration amongst greening project team members                          |
| RF36| Lack of support from organizations developing GB standards and rating systems                          |
| RF37| Poor processing and management of GB related information                                              |
| RF38| Unclear criteria to make a decision of either demolish-and-build practice or renovation for GEB      |
Table 3. Cont.

| No. | Risk Factor (G05) |
|-----|-------------------|
| RF39 | Lack of clarity in the responsibility of greening process and certification |
| RF40 | Difficulty in comprehending green specifications in contract details due to possible ambiguities and conflicts between clauses |
| RF41 | Ownership type not obliged or giving attention to GB and sustainability issues |
| RF42 | Inaccurate orientation of greening project’s goal |
| RF43 | Lack of adequate planning along with unclear GB long-term and life cycle perspective |

5. Green Building (GB) and Sustainability Operation (G05)

| No. | Risk Factor (G06) |
|-----|-------------------|
| RF44 | High level of water use during operation |
| RF45 | Irregular GB services and performance monitoring |
| RF46 | High energy use during operation |
| RF47 | Excessively complex codes, regulations, and rating systems of GB during operation |
| RF48 | Ineffective environmental compliance and auditing plans |
| RF49 | Lack of stability in GB operation performance |
| RF50 | Lack of adequate GB maintenance |
| RF51 | Ineffective use of functional spaces such as green parking |
| RF52 | Misunderstanding of green technological operations |

6. Greening Process Design-Related Risks (G06)

| No. | Risk Factor (G06) |
|-----|-------------------|
| RF53 | Inappropriate use of accurate calculation-based design approaches with little feedback from performance monitoring |
| RF54 | Unsuitability of building type, size, age, or site conditions to accommodate green feature and technology |
| RF55 | Poor level of integration of GB innovative design approaches such as adopting smart building technology |
| RF56 | Wrong timing for involving GB stakeholders in the design stage |
| RF57 | Poor level of design innovation |
| RF58 | Unsuitable choice of equipment, strategies, and design systems that lead to intensive energy consumption and low comfort levels |
| RF59 | Insufficient green space consideration |
| RF60 | Incompatible GB design features with rating and assessment standards |
| RF61 | High frequency of design alterations and variations during the greening design process |

7. Greening Process Renovation and Construction Stage Risks (G07)

| No. | Risk Factor (G07) |
|-----|-------------------|
| RF62 | Lack of contractor’s/subcontractor’s familiarity with GB-related responsibilities |
| RF63 | Lack of sufficient time and management to address sustainability issues, and possible delays |
| RF64 | Limited availability and reliability of green suppliers that creates procurement and tendering difficulty |
| RF65 | Unforeseen in circumstances and construction accidents in executing green projects |
| RF66 | Difficult construction site control conditions |

5. Application of RAMGEB

Field surveys were conducted to collect data concerning the identified 66 risk factors in Saudi Arabia for the purpose of model application and verification. The collected data regarding the three characteristics of risks affecting GEB were collected through a brainstorming session conducted online with seven specialists who have experience in the field of green building execution and sustainability evaluation for data collection with regard to risk factor characteristics (RFP, IGEB, and IBP). The results of this session are summarized in the first three columns in Table 4, which represent the inputs of the model.
### Table 4. RAMGE inputs and output and risk factors prioritized based on ranking in all indices.

| No.  | RFP | IGEB | IBP | FIGEB | RFP | IGEB | IBP | FIGEB |
|------|-----|------|-----|-------|-----|------|-----|-------|
| RF16 | 0.71| 0.72 | 0.84 | 0.793 | 3   | 12   | 1   | 1     |
| RF18 | 0.66| 0.67 | 0.81 | 0.716 | 7   | 16   | 5   | 2     |
| RF53 | 0.51| 0.78 | 0.82 | 0.71  | 21  | 3    | 2   | 3     |
| RF12 | 0.68| 0.49 | 0.73 | 0.673 | 4   | 54   | 18  | 4     |
| RF19 | 0.48| 0.77 | 0.81 | 0.664 | 40  | 8    | 4   | 5     |
| RF21 | 0.62| 0.67 | 0.66 | 0.646 | 12  | 17   | 20  | 6     |
| RF59 | 0.64| 0.65 | 0.66 | 0.641 | 10  | 21   | 22  | 7     |
| RF17 | 0.51| 0.64 | 0.64 | 0.633 | 22  | 22   | 26  | 8     |
| RF41 | 0.49| 0.64 | 0.65 | 0.633 | 32  | 24   | 23  | 9     |
| RF37 | 0.51| 0.63 | 0.81 | 0.62  | 23  | 27   | 7   | 10    |
| RF43 | 0.5 | 0.64 | 0.81 | 0.619 | 29  | 23   | 6   | 11    |
| RF24 | 0.48| 0.61 | 0.63 | 0.608 | 41  | 30   | 32  | 12    |
| RF32 | 0.48| 0.78 | 0.61 | 0.608 | 42  | 5    | 38  | 13    |
| RF28 | 0.48| 0.6  | 0.63 | 0.6   | 43  | 32   | 33  | 14    |
| RF30 | 0.48| 0.6  | 0.6  | 0.6   | 44  | 33   | 39  | 15    |
| RF36 | 0.4 | 0.59 | 0.59 | 0.596 | 51  | 39   | 41  | 16    |
| RF23 | 0.49| 0.59 | 0.64 | 0.592 | 33  | 37   | 27  | 17    |
| RF25 | 0.41| 0.59 | 0.62 | 0.592 | 49  | 38   | 35  | 18    |
| RF27 | 0.51| 0.59 | 0.65 | 0.592 | 24  | 36   | 24  | 19    |
| RF06 | 0.47| 0.61 | 0.58 | 0.587 | 47  | 31   | 43  | 20    |
| RF29 | 0.49| 0.58 | 0.64 | 0.584 | 34  | 43   | 28  | 21    |
| RF39 | 0.5 | 0.58 | 0.65 | 0.584 | 30  | 42   | 25  | 22    |
| RF20 | 0.35| 0.79 | 0.78 | 0.574 | 60  | 2    | 13  | 23    |
| RF54 | 0.52| 0.79 | 0.48 | 0.574 | 18  | 1    | 46  | 24    |
| RF51 | 0.36| 0.78 | 0.63 | 0.571 | 57  | 6    | 30  | 25    |
| RF54 | 0.36| 0.74 | 0.77 | 0.569 | 58  | 11   | 17  | 26    |
| RF60 | 0.36| 0.75 | 0.77 | 0.569 | 59  | 10   | 16  | 27    |
| RF26 | 0.41| 0.55 | 0.63 | 0.566 | 50  | 45   | 34  | 28    |
| RF33 | 0.35| 0.78 | 0.63 | 0.566 | 61  | 7    | 31  | 29    |
| RF40 | 0.5 | 0.78 | 0.35 | 0.563 | 31  | 4    | 55  | 30    |
| RF38 | 0.81| 0.67 | 0.34 | 0.562 | 1   | 15   | 59  | 31    |
| RF01 | 0.79| 0.66 | 0.34 | 0.556 | 2   | 18   | 60  | 32    |
| RF14 | 0.54| 0.61 | 0.48 | 0.556 | 15  | 29   | 47  | 33    |
| RF05 | 0.28| 0.66 | 0.78 | 0.543 | 64  | 20   | 14  | 34    |
| RF13 | 0.68| 0.69 | 0.33 | 0.538 | 8   | 13   | 61  | 35    |
| RF07 | 0.39| 0.52 | 0.39 | 0.532 | 52  | 48   | 42  | 36    |
| RF15 | 0.39| 0.52 | 0.52 | 0.532 | 53  | 49   | 44  | 37    |
| RF28 | 0.51| 0.52 | 0.67 | 0.527 | 25  | 46   | 19  | 38    |
| RF08 | 0.38| 0.51 | 0.62 | 0.517 | 56  | 53   | 36  | 39    |
| RF10 | 0.51| 0.51 | 0.47 | 0.514 | 26  | 50   | 49  | 40    |
| RF04 | 0.29| 0.66 | 0.66 | 0.49  | 62  | 19   | 21  | 41    |
| RF22 | 0.49| 0.51 | 0.47 | 0.486 | 35  | 52   | 50  | 42    |
| RF03 | 0.49| 0.68 | 0.35 | 0.485 | 36  | 14   | 56  | 43    |
| RF35 | 0.52| 0.49 | 0.46 | 0.485 | 19  | 55   | 51  | 44    |
| RF42 | 0.51| 0.49 | 0.46 | 0.485 | 27  | 56   | 52  | 45    |
| RF55 | 0.49| 0.44 | 0.62 | 0.483 | 37  | 57   | 37  | 46    |
| RF09 | 0.28| 0.59 | 0.51 | 0.477 | 65  | 41   | 45  | 47    |
| RF56 | 0.48| 0.64 | 0.35 | 0.471 | 45  | 25   | 57  | 48    |
| RF61 | 0.48| 0.64 | 0.35 | 0.471 | 46  | 26   | 58  | 49    |
| RF02 | 0.47| 0.6 | 0.48 | 0.466 | 48  | 34   | 48  | 50    |
| RF44 | 0.66| 0  | 0.79 | 0.444 | 8   | 59   | 10  | 51    |
| RF46 | 0.66| 0  | 0.82 | 0.433 | 9   | 60   | 3   | 52    |
| RF52 | 0.67| 0  | 0.64 | 0.432 | 6   | 58   | 29  | 53    |
| RF57 | 0.29| 0.63 | 0.38 | 0.422 | 63  | 28   | 53  | 54    |
| RF50 | 0.63| 0  | 0.81 | 0.411 | 11  | 61   | 8   | 55    |
| RF45 | 0.53| 0  | 0.8  | 0.382 | 17  | 65   | 9   | 56    |
Table 4. Cont.

| No. | Index Value | Rank Due To |
|-----|-------------|-------------|
|     | RFP | IGEB | IBP | FIGEB | RFP | IGEB | IBP | FIGEB |
| RF11 | 0.16 | 0.58 | 0.38 | 0.38 | 66 | 44 | 54 | 57 |
| RF48 | 0.55 | 0 | 0.79 | 0.374 | 13 | 62 | 11 | 58 |
| RF49 | 0.54 | 0 | 0.79 | 0.374 | 16 | 64 | 12 | 59 |
| RF51 | 0.55 | 0 | 0.78 | 0.366 | 14 | 63 | 15 | 60 |
| RF64 | 0.49 | 0.76 | 0 | 0.351 | 38 | 9 | 62 | 61 |
| RF63 | 0.52 | 0.59 | 0 | 0.332 | 20 | 35 | 63 | 62 |
| RF66 | 0.51 | 0.51 | 0 | 0.316 | 28 | 51 | 66 | 63 |
| RF47 | 0.39 | 0 | 0.6 | 0.3 | 54 | 66 | 40 | 64 |
| RF62 | 0.49 | 0.52 | 0 | 0.3 | 39 | 47 | 65 | 65 |
| RF65 | 0.39 | 0.59 | 0 | 0.3 | 55 | 40 | 64 | 66 |

|   | RFP = RF Presence | IGEB = Impact on GEB | IBP = Impact on Building Performance in the Long Run | FIGEB = Fuzzy Index for GEB |

The collected data regarding the assessment of the identified risk factors are presented in the form of five risk levels (very high, high, medium, low, and very low). These indices were utilized to order the risk factors based on their RFP, IGEB, and IBP as determined by the participants in the brainstorming session. Clarification of the mentioned indices is presented in the following equations:

\[
RFP = \frac{\sum_{i=1}^{5} P_i \times N_i}{\sum_{i=1}^{5} N_i} \quad (1)
\]

\[
IGEB = \frac{\sum_{i=1}^{5} I_{gebi} \times N_i}{\sum_{i=1}^{5} N_i} \quad (2)
\]

\[
IBP = \frac{\sum_{i=1}^{5} I_{bpi} \times N_i}{\sum_{i=1}^{5} N_i} \quad (3)
\]

where:

- RFP represents the presence of a risk factor;
- \( P_i \) represents the probability weight (presence weight);
- \( N_i \) is the number of participants who responded to option \( I \);
- IGEB represents the impact of a risk factor on GEB;
- Igebi represents the impact weight for GEB;
- IBP represents the impact of a risk factor on building performance in the long run;
- Ibpi represents the impact weight for building performance in the long run.

The weight for \( P_i, I_{gebi}, \) and \( I_{bpi} \) can be expressed by the values 0.1, 0.3, 0.5, 0.7, and 0.9 for the \( i \) response (1, 2, 3, 4, or 5, respectively).

The output of the model (FIGEB) was calculated and presented in Table 4 (column 4). All factors were ranked on the basis of their FIGEB, and the ranks based on the three inputs were also determined. It can be noted from this table that RF16 (low response of GB to local geography and climatic conditions due to insufficient on-site environmental investigations) is considered the most important risk factor based on its overall importance due to its FIGEB value. It is also ranked first in terms of its effect on the building performance in the long run (IBP), and although it is in twelfth place regarding its effect on GEB (IGEB), it occupies third place in terms of presence (RFP).

RF38 (unclear criteria to make a decision between either demolish-and-build practice or renovation for GEB) is considered the most important risk factor in terms of presence. However, it places 31st in the overall ranking regarding FIGEB and 59th in terms of IBP. On the other hand, RF54 (unsuitability of building type, size, age, or site conditions to accommodate green features and technology) is in 1st place in terms of IGEB, and 18th, 46th, and 24th in regard to RFP, IGEB, and IBP, respectively.
Many risk factors can be neglected due to their low FIGEB values and low rank, such as R62 and R65 (lack of contractor’s/subcontractor’s familiarity with GB-related responsibilities and unforeseen circumstances and construction accidents in executing green projects). More details and analyses are provided in the section regarding key risk factors.

6. Model Verification

Risk factors can be ranked according to their severity index values by calculating the severity risk index affecting GEB for all risk factor characteristics using the following equation:

\[ SR_{GEB} = FR_P \times IG_{EB} \times IB_P \]  

The results of applying the model for the sixty-six risk factors affecting GEB in Saudi Arabia were obtained by calculating FIGEB. A correlation coefficient test was introduced using Spearman’s test for ranking the factors on the basis of FIGEB and SRGEB. The correlation coefficient factor was calculated, and its value was 0.946, representing a highly positive correlation between FIGEB and SRGEB and thereby verifying the model results.

7. Case Study Results and Discussion

7.1. Analysis of Risk Groups

Many statistical tests can be conducted to evaluate and compare the identified risk groups affecting GEB. In Table 3, it can be observed that the maximum number of risk factors was categorized in Group 03 (greening process of environmental control risks), which contains 15 risk factors, while Group 07 (greening process of renovation and construction stage risks) is affected by five risk factors, representing the minimum number of risk factors. Tables 5 and 6 summarize the mean values and range values for risk, respectively. Figure 3 shows the boxplot analysis for the seven groups based on FIGEB values. The boxplot graph is considered a fast, graphic summary that simply presents many statistical characteristics, such as the center, spread, range, and points locating the outliers, which are represented by a small circle above or below the range [53]. The box represents half of the analyzed data, while the 75th percentile and 25th percentile appear at the upper and lower edges of the box, respectively. A line drawn in the middle of the box represents the median.

Table 5. Mean values for all risk groups.

| Risk Group | G01   | G02   | G03   | G04   | G05   | G06   | G07   |
|------------|-------|-------|-------|-------|-------|-------|-------|
| RFP        | 0.427 | 0.493 | 0.504 | 0.484 | 0.575 | 0.475 | 0.48  |
| IGEB       | 0.68  | 0.566 | 0.632 | 0.661 | 0     | 0.649 | 0.594 |
| IBP        | 0.545 | 0.485 | 0.67  | 0.567 | 0.758 | 0     | 0.56  |
| FIGEB      | 0.157 | 0.532 | 0.616 | 0.574 | 0.391 | 0.541 | 0.32  |

Table 6. Range values for all risk groups.

| Risk Group | G01   | G02   | G03   | G04   | G05   | G06   | G07   |
|------------|-------|-------|-------|-------|-------|-------|-------|
| RFP        | 0.51  | 0.52  | 0.36  | 0.46  | 0.28  | 0.35  | 0.13  |
| IGEB       | 0.17  | 0.2   | 0.28  | 0.29  | 0     | 0.35  | 0.25  |
| IBP        | 0.44  | 0.4   | 0.37  | 0.47  | 0.22  | 0.47  | 0     |
| FIGEB      | 0.12  | 0.29  | 0.31  | 0.15  | 0.14  | 0.29  | 0.05  |

In Figure 3, it can be seen that the maximum mean value is for G05 in the case of both RFP and IBP, while the maximum mean value in the case of IGEB is for G04. On the other hand, the maximum value of FIGEB is for G03.

In Figure 3 and Table 6, the range values for risk groups can be analyzed and compared. For RFP, the maximum range is for G02, and the minimum is for G07. For IGEB, the maximum range is for G06, and the minimum is for G05. In the case of IBP, the extreme range is for G04 and G06. Lastly, for FIGEB, the maximum range is for G03, and the minimum is for G07. It can be observed that although G03 contains the maximum number
of risk factors (15 factors), it cannot be characterized by the largest range in all cases, except in FIGEB. This result reflects the good effect of using the model.

![Boxplot analysis comparing the seven risk groups based on FIGEB.](image1)

**Figure 3.** Boxplot analysis comparing the seven risk groups based on FIGEB.

7.1.1. Group 01 (Greening Process of Economical Risks)

Group 01 includes nine risk factors related to economic conditions and that affect GEB. Figure 4, it can be observed that the values in the case of IBP are divergent. On the other hand, in RFP, there is one outlier factor in the case of RFP (RF01: high overall cost and budget of GEB, including materials, products, and technology), and the remaining factors are close in terms of their values. The values are close in the case of FIGEB. The most important risk factor in this group due to the combined effect (FIGEB) is RF06 (high cost of conducting a green building standard assessment), which came 20th in the overall ranking.

![Box plot for inputs and output of the RAMGEB in the case of Group 01.](image2)

**Figure 4.** Box plot for inputs and output of the RAMGEB in the case of Group 01.
7.1.2. Group 02 (Greening Process of Social Risks)

There are six risk factors that belong to the social aspects in Group 02. In Figure 5, it can be seen that the maximum range is for RFP, followed by IBP. The riskiest factor in this group according to its FIGEB is RF12, which has an overall rank of 4.

![Figure 5. Box plot for inputs and output of the RAMGEB in the case of Group 02.](image)

7.1.3. Group 03 (Greening Process of Environmental Control Risks)

In Group 03, which contains the maximum number of risks due to environmental control, it can be observed from Figure 6 that in the case of RFP, there are six outlier risk factors, which suggests inconsistent distribution and high variation in the presence of these factors. Furthermore, these outlier factors are limited to only two using the RAMGEB, which combines the three characteristics of a risk factor. Moreover, RF22 (inability of the greening process to preserve existing natural environment within the GB site) is an outlier in the cases of IBP and FIGEB. RF16 (low response of GB to local geography and climatic conditions due to insufficient on-site environmental investigations) appears to be the most important risk factor in overall risks, not only in this group, and it is in first place due to its high FIGEB value. Furthermore, this group, due to its large number of risk factors, is considered the riskiest group.

![Figure 6. Box plot for inputs and output of the RAMGEB in the case of Group 03.](image)
7.1.4. Group 04 (Greening Process of Managerial Risks)

Group 04 contains 13 managerial risk factors, which have various effects on the GEB process. Observing Figure 7, it can be noted that the limit of FIGEB due to the use of the model reduces the three input ranges to smaller values. The most significant risk factor in this group due to its FIGEB value is RF41 (ownership type not obliged or giving attention to GB and sustainability issues), which occupies ninth place in the overall ranking.

7.1.5. Group 05 (Green Building and Sustainability Operation)

Although Group 05 contains nine risk factors affecting the operation process, due to the experts’ opinions, it has no effect on the GEB stage. Thus, the model combined only RFP and IBP, neglecting IGEB, which led to a decrease in FIGEB values. Observing Figure 8, it is clear that the IBP values are higher than those of the other indices’ values. The most important risk factor in this group due to FIGEB is RF44 (high-level water use during operation), and its overall rank is 55th. This suggests that the effect of this risk group is low.

Figure 7. Box plot for inputs and output of the RAMGEB in the case of Group 04.

Figure 8. Box plot for inputs and output of the RAMGEB in the case of Group 05.
7.1.6. Group 06 (Greening Process of Design-Related Risks)

Nine risk factors are categorized in Group 06. It is clear from Figure 9 that the ranges and values for all inputs and the output are close. The most important risk factor in this group according to the FIGEB value is RF53 (inappropriate use of accurate calculation-based design approaches with little feedback from performance monitoring), which occupies third place in the overall ranking.

![Box plot for inputs and output of the RAMGEB in the case of Group 06.](image)

**Figure 9.** Box plot for inputs and output of the RAMGEB in the case of Group 06.

7.1.7. Group 07 (Greening Process of Renovation and Construction Stage Risks)

Group 07 contains the minimum numbers of risk groups (five risk factors), and it does not affect the building performance in the long run according to the experts’ opinions. Observing Figure 10, it can be suggested that the FIGEB values are low due to the lack of effect on IBP. The most important risk factor in this group due to its FIGEB value is RF64 (limited availability and reliability of green suppliers, which makes procurement and tendering difficult), which ranked in sixth place, which confirms that this is the least risky group when compared to the other groups.

![Box plot for inputs and output of the RAMGEB in the case of Group 07.](image)

**Figure 10.** Box plot for inputs and output of the RAMGEB in the case of Group 07.

7.2. Key Risk Factors Affecting GEB in Saudi Arabia

All risk factors observed in the investigation study may occur and affect GEB. To evaluate the significant risk factors, it is important to identify the risks whose high expected values should be determined and highlighted. Hence, the top ten ranked risks are proposed as key indicators in all input and output indices. The highest ten risk factors are summarized in Table 7 and rated based on their FIGEB.
7.2. Key Risk Factors Affecting GEB in Saudi Arabia

All risk factors observed in the investigation study may occur and affect GEB. To evaluate the significant risk factors, it is important to identify the risks whose high expected values should be determined and highlighted. Hence, the top ten ranked risks are proposed as key indicators in all input and output indices. The highest ten risk factors are summarized in Table 7 and rated based on their FIGEB.

Table 7. Key risk factors affecting GEB in Saudi Arabia.

| Rank | RF No. | Index Value | Group | RF No. | Index Value | Group | RF No. | Index Value | Group | FIGEB | Index Value | Group |
|------|--------|-------------|-------|--------|-------------|-------|--------|-------------|-------|-------|-------------|-------|
| 1    | RF38   | 0.81        | G04   | RF20   | 0.79        | G03   | RF16   | 0.84        | G03   | RF16   | 0.793       | G03   |
| 2    | RF51   | 0.79        | G01   | RF54   | 0.79        | G06   | RF53   | 0.82        | G06   | RF18   | 0.716       | G03   |
| 3    | RF53   | 0.78        | G06   | RF16   | 0.82        | G05   | RF53   | 0.71        | G06   | RF33   | 0.78        | G04   |
| 4    | RF16   | 0.81        | G03   | RF53   | 0.78        | G06   | RF19   | 0.81        | G03   | RF12   | 0.673       | G02   |
| 5    | RF12   | 0.79        | G02   | RF31   | 0.78        | G04   | RF19   | 0.81        | G03   | RF19   | 0.664       | G03   |
| 6    | RF18   | 0.66        | G03   | RF39   | 0.78        | G04   | RF18   | 0.81        | G03   | RF21   | 0.646       | G03   |
| 7    | RF13   | 0.68        | G02   | RF31   | 0.78        | G04   | RF18   | 0.81        | G03   | RF59   | 0.641       | G06   |
| 8    | RF52   | 0.66        | G05   | RF40   | 0.78        | G04   | RF37   | 0.81        | G04   | RF17   | 0.633       | G03   |
| 9    | RF19   | 0.79        | G03   | RF50   | 0.81        | G05   | RF41   | 0.633       | G04   |         |             |       |
| 10   | RF59   | 0.64        | G06   | RF60   | 0.75        | G06   | RF44   | 0.79        | G05   | RF37   | 0.62        | G04   |

As previously mentioned, RF16 is in first place in the ranking due to its FIGEB value; however, it is not among the top ten factors in regard to IGEB values. The risk factor in second place in this ranking is RF18, but it is not among the top ten risks due to its IGEB value. RF3 is third in the overall order, but it is not among the top ten RFP factors. It can be observed that five risk factors among the highest ten in regard to FIGEB values belong to G03. A number of risk factors occupying the top ten placements in regard to FIGEB, such as RF21, R17, and RF41, do not appear in any of the inputs in the other indices. This confirms the importance of the model in regard to combining many effects.

7.3. Risk Index Correlations

A statistical test is recommended to show the direction and strength of the relationships amongst risk indices that affect GEB. Spearman’s rank correlation coefficient is used to determine such relations. It compares medians rather than means and gives better results if the data have one or two outliers. Spearman’s rank correlation coefficient \( R \) ranges from \(-1\) to \(+1\). If \( R = +1 \), then there is wide-ranging agreement in the order of the ranks, and the ranks are in the same direction. If \( R = -1 \), then there is a complete agreement in the order of the ranks, and the ranks are in the opposite direction. If \( R = 0 \), then there is no correlation. In this study, Spearman’s correlation coefficient was used among inputs in the arrangement of RFP, IGEB, and IBP and the output, which is FIGEB.

Figure 11 reviews the results of the Spearman’s test via the determined correlation coefficient values. The highest positive correlation is between IGEB and FIGEB, which suggests that IGEB is the most important input affecting the output, followed by IBP, while there is no relation between RFP and FIGEB. This indicates that with the increase in IGEB, IBP also increases. On the other hand, there is a small adverse relation between RFP and IGEB.
8. Summary and Conclusions

The adoption of existing building performance through the greening process can mitigate negative impacts on the environment, and it has been recognized as a crucial step towards global sustainable development. While the numerous benefits of green construction have been widely predicted, the risks associated with the greening process have not been appropriately addressed. This study proposed and developed a model based on the fuzzy logic technique to address and evaluate the risks that affect GEB. Three parameters representing the risk factor features were introduced: risk presence and their effect on the greening process and building performance in the long run. In addition, a new risk index making associations between the three parameters was quantified. Several linguistic variables were used by applying various logical rules in order to achieve a relation between the inputs and output. The model was verified by applying it in the context of Saudi Arabia as a case study.

The main findings of this study include the following points:

1. The proposed model improved the evaluation process for risk factors affecting GEB. This was clearly due to the minimization of the number of outlier risk factors in the inputs and the decrease in the input ranges when compared to those of the output. Additionally, some highly ranked risk factors, due to their overall effects, did not appear in the key risks in some input parameters.

2. The results of the proposed model can be used as an important criterion to support decision makers in evaluating the main issues that GEB faces. This can also help in comparing more than one greening project based on risk analysis.

3. The presented model is not limited to the context of Saudi Arabia but can be applied in all countries using minor modifications. Using the fuzzy logic concept added flexibility and ease of use in managing the problem.

Further conclusions were made by applying the model to the investigated case study in Saudi Arabia:

4. The major risk sources were presented in terms of their presence and impacts on the GEB stage and on building performance in the long run. Many risk factors should be considered due to their considerable effects on GEB, such as RF16, RF18, and RF53. Conversely, many risk factors can be ignored due to their minimal effects, such as RF65, RF62, and RF47.

Figure 11. Correlation coefficients among risk indices.
5. Group 03, which depends on the greening process of environmental control risks, is considered the most imperative risk group because it includes many top key risk factors due to their high FIGEB values, and it represents the maximum range in all groups.

6. FIGEB shares a positive relationship with both IGEB and IBP, while there is no relationship between RFP and FIGEB.

7. There are many variations among the risk factors and risk groups related to the different characteristics. For example, the maximum mean value for G05 is in the case of RFP and IBP, while the maximum mean value in the case of IGEB is for G04. On the other hand, the maximum value of FIGEB is for G03.

8. The sustainability operation risk group has no effect on GEB, while the greening process of renovation and construction stage risk group has no effect on building performance in the long run.

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