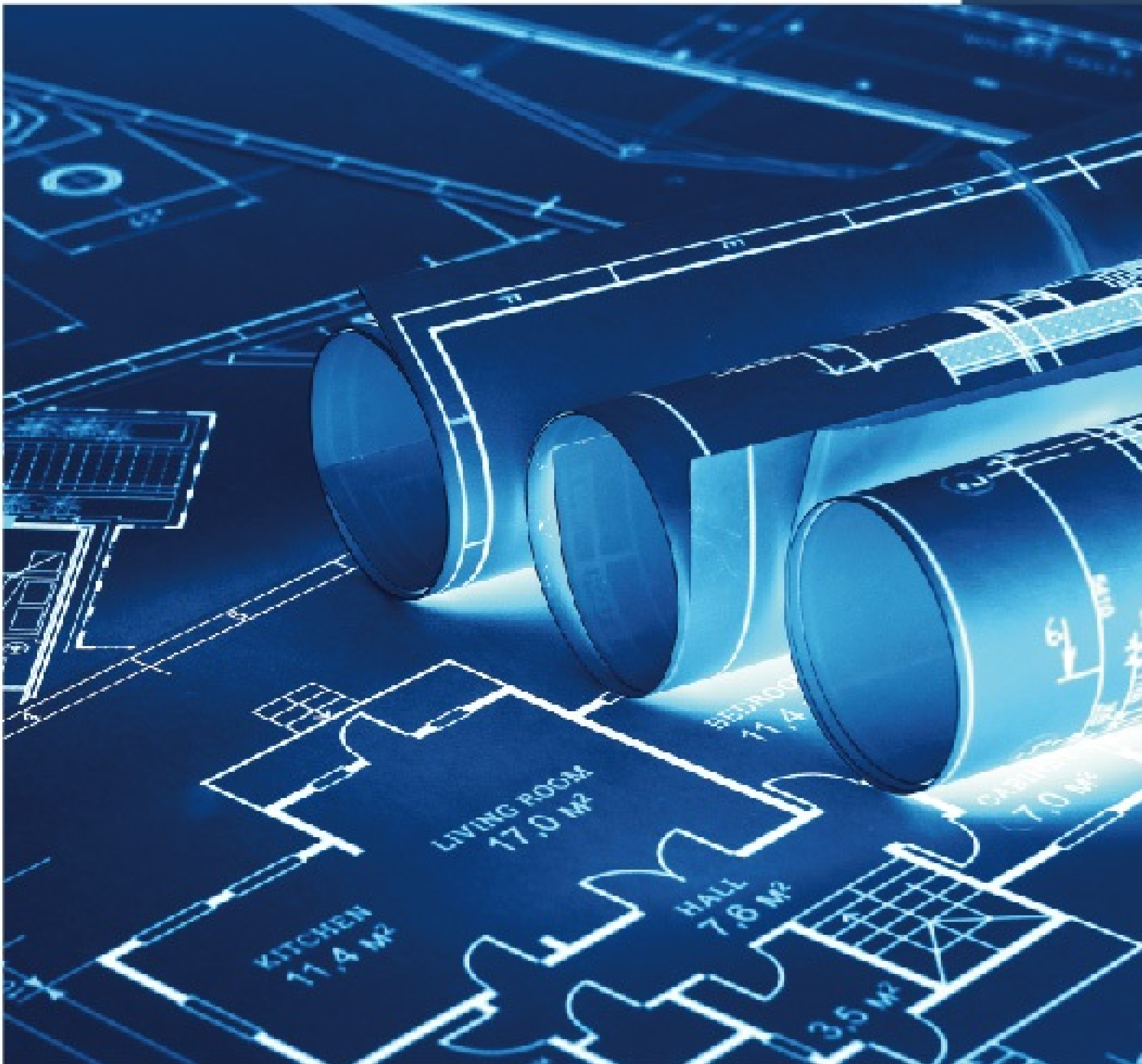
Building Engineering

http://ojs.acad-pub.com/index.php/BE

ACADEMIC

2024 VOLUME 2 ISSUE 2
ISSN: 3029-2670 (Online)



2

Editorial Team

Rosa Agliata
Universitas Mercatorum; Università della Campania
Italy

Parsa Ghannadi
Islamic Azad University
Iran

Jolanta Tamošaitienė
Vilnius Gediminas technical university - Vilnius TECH
Lithuania

Volume 2 Issue 2 • 2024

Building Engineering

Editor-in-Chief

Prof. Scholz Miklas

University of Johannesburg, South Africa

ACADEMIC
ACADEMIC PUBLISHING PTE LTD

2024 | Volume 2 | Issue 2

Building Engineering

https://ojs.acad-pub.com/index.php/BE

Contents

Articles

Reviews

Building Engineering 2024, 2(2), 1316.
https://doi.org/10.59400/be.v2i2.1316

Article

An analysis of the Puri Brata Resort & Gallery building's design from an environmental aesthetics and sustainability perspective

Hermawan Hermawan[1,*], Amin Safa'at[1], Nabila Arrizqi Annisa[2]

[1] Department of Architecture, Universitas Sains Al-Qur'an, Wonosobo 56351, Indonesia
[2] Department of Civil Engineering, Universitas Islam Indonesia, Yogyakarta 55584, Indonesia
*** Corresponding author:** Hermawan Hermawan, hermawanarsit@gmail.com

CITATION

Hermawan H, Safa'at A, Annisa NA. An analysis of the Puri Brata Resort & Gallery building's design from an environmental aesthetics and sustainability perspective. Building Engineering. 2024; 2(2): 1316. https://doi.org/10.59400/be.v2i2.1316

ARTICLE INFO

Received: 22 April 2024
Accepted: 3 July 2024
Available online: 17 July 2024

Abstract: The research paper delves into the implementation of sustainable architectural design practices at Puri Brata Resort & Gallery in Yogyakarta, Indonesia. The primary objective of the study is to analyze the impact of eco-friendly design principles on both the environment and visitor experience within the resort. Data collection for this research involved conducting a comprehensive survey among visitors to the resort, focusing on aspects such as air quality, temperature control, and overall visitor comfort. Additionally, data was gathered on the utilization of green spaces within the resort and the incorporation of local cultural values and aesthetics in the architectural design. The survey responses were then analyzed to evaluate the perceived impact of sustainable design elements on the guest experience and environmental sustainability. The findings of the research indicate that the integration of eco-friendly practices at Puri Brata Resort & Gallery has positively impacted various aspects, including improved air quality, efficient temperature control, and enhanced visitor comfort. The use of recycled materials, renewable energy sources, and green spaces has contributed to creating a harmonious and sustainable environment that enhances the overall guest experience. The study underscores the importance of incorporating sustainable design principles in architectural practices to create spaces that benefit both the environment and visitors. This research provides valuable insights for industry practitioners and policymakers looking to adopt sustainable design practices in the hospitality and tourism sector.

Keywords: sustainable architectural design; environmental aesthetics; cultural heritage; hospitality industry

1. Introduction

In an increasingly advanced era, sustainability and environmental conservation have become pressing global issues, particularly for the hospitality and tourism industry. It cannot be denied that the hospitality and tourism industry significantly contributes to the economy; however, the development and operation of this industry often negatively impact the environment. One of the negative impacts arising from the hospitality and tourism industry is environmental degradation. This is due to the use of environmentally unfriendly building designs which result in excessive energy and water consumption, thus triggering waste production and the use of unsustainable materials [1]. Currently, the hospitality and tourism industry contributes to 8% of global greenhouse gas emissions, necessitating a reduction in water usage by up to 30% and energy consumption by up to 50% [2–4].

These problems are caused by a lack of awareness, cost limitations, and inadequate regulations and policies. The long-term effects of these issues can lead to environmental damage, climate change, water shortages, health problems, and a decline in the industry's reputation. Therefore, it is essential to implement green building designs to reduce energy use, water consumption, and sustainable materials.

Green architecture strategies play an important role in reducing the negative impacts of environmental degradation through the use of natural lighting and ventilation, energy efficiency, and natural materials [5]. According to Tri Harsono Karyono, three targets that an architectural work should fulfill are: aesthetic demands, comfort (both psychological and physical), and energy saving. Therefore, implementing green architecture strategies for the hospitality and tourism industry will create a more environmentally friendly sector [6].

Building designs that consider greenness and environmental aesthetics are important for preserving natural ecosystems and enhancing the quality experience for visitors. A hotel or resort should be able to create a design that responds to the climatic conditions of its location [7]. In the development of resort areas, ecological principles are applied by arranging buildings to create open spaces adorned with active gardens [8].

Integrating buildings with their natural surroundings, using local elements, and respecting cultural heritage are elements that can enhance the aesthetic value of a building. The field of sustainable building design has concluded that the adoption of environmentally supportive features positively impacts both the building and its environment. The use of recycled materials, the utilization of renewable energy, and efficient water management systems have been proven to reduce negative environmental impacts [9].

In facing global sustainability challenges, the hospitality and tourism industry must adopt green building designs to mitigate negative environmental impacts. Designs that consider energy and water efficiency and the use of sustainable materials are not only important for maintaining natural ecosystems but also for enhancing visitor experiences.

This research aims to analyze the building design of Puri Brata Resort & Gallery from the perspective of greenness and environmental aesthetics. The study is limited to the location of Puri Brata Resort & Gallery and does not include other sensory aspects such as sound or aroma, nor does it include the economic sustainability aspects of building design in its analysis.

2. Literature review

2.1. Sustainability in architecture

Sustainability in architecture has become a crucial topic in academic literature and professional practice, focusing on creating buildings that are efficient and environmentally friendly [10]. Sustainable architectural design not only reduces environmental impact but also enhances the energy efficiency of buildings [11]. Recent research indicates that sustainability aspects should be considered from the early planning stages and continue through the selection of sustainable materials for construction projects [12,13].

The importance of sustainability in architectural education has been emphasized, with architects worldwide taking on the responsibility to act against climate change and adhere to the United Nations Sustainable Development Goals (SDGs) in both practice and education [10]. Additionally, selecting sustainable materials is a complex process that must consider various parameters for a certified green project [14]. This research underscores the importance of choosing materials that are not only environmentally friendly but also support the overall performance of buildings [15].

Thus, this literature review shows that sustainable architectural design is a comprehensive approach that requires careful consideration at every project stage, from planning to material selection, to achieve optimal results in terms of sustainability and efficiency [16].

Environmental aesthetics in building design

The aesthetic environment plays a crucial role in building design, where the harmony between artificial structures and the surrounding nature not only enriches the user's visual experience but also supports the principles of sustainability [17]. Design that takes into account the characteristics of the surrounding environment can create buildings that not only visually integrate with their landscape but also contribute to ecological and social well-being [18].

The concept of environmental aesthetics in building design emphasizes the importance of creating a harmonious relationship between buildings and their natural surroundings. This includes the use of shapes, colors, and materials that respect and highlight the beauty of nature [19]. Moreover, this approach also considers how the building interacts with natural elements such as light, wind, and vegetation, thus creating a healthy and comfortable environment for its users [20].

Recent research in international journals indicates that the integration of environmental aesthetics in building design not only enhances visual value but also supports sustainability by reducing environmental impact and increasing energy efficiency [21]. Therefore, this literature review underscores that building design that considers environmental aesthetics represents the state-of-the-art in sustainable architecture aimed at achieving a balance between human needs and the preservation of nature [22].

To unravel the complex relationship between environmental aesthetics and sustainability in building design, a growing body of research has emerged. These studies frequently share common ground in their thematic concerns while employing diverse methodological approaches and delving into distinct aspects of the subject matter.

The implementation of green architecture strategies in the hospitality and tourism industries has become an important highlight. Emphasizing green tourism practices for the long-term sustainability of tourism destinations at White Beach, Puerto Galera, is emphasized. By applying theories of green practice, hotels and resorts can enhance their efforts in waste management, utilize environmentally friendly energy technology, support government programs related to water management, and educate guests on the importance of waste reduction. The cooperation among hotel owners, managers, staff, local tourists, and foreign tourists is also deemed crucial in implementing green practices. The adoption of energy-saving technology and practices by hotels and resorts can reduce environmental impact while supporting environmental sustainability [23].

The principles of sustainability in sustainable architecture include efficient use of energy, land, and materials, utilization of new technologies and materials, as well as effective waste management. A holistic approach in sustainable architecture addresses green restoration, the creation of a comfortable environment, and efforts to reduce environmental burdens. Focus on building characteristics, such as mass shape and orientation towards the sun, is highlighted in this study. The intention behind developing sustainable architecture is to achieve sustainability from economic, social, and environmental aspects [24].

The importance of sustainable business practices is highlighted by Rana [25] in the referenced journal. In it, the required commitment to uphold the core values of sustainable development is revealed. Sustainable business strategies are aimed at achieving economic, social, and environmental goals simultaneously. Through the research, it is emphasized that sustainability as a core principle offers sustainable profitability and a competitive edge for companies. The research results highlight the close relationship between sustainability and financial success in the business realm [25].

Sustainable practices in the Egyptian tourism industry become a crucial focus, especially in planning and designing eco-friendly resorts. The case of Marina el-Alamien illustrates the negative impact of unsustainable development on valuable natural heritage in an area. Although Egypt has abundant natural resources, industrial and economic factors have triggered inefficient resource use and environmental degradation in sensitive areas. Hence, the need for sustainable practices in the tourism industry becomes more urgent to preserve environmental sustainability and the rich natural heritage [26].

Sustainable resort development becomes the primary focus in the tourism industry. This research highlights the importance of using a sustainability index to assess the level of sustainable development in tourism services and the need to consider social, economic, environmental, and human impacts in developing sustainable resorts. With the continuously growing tourism industry, sustainability and resilience in resort development become vital. Through modern approaches and proper use of indicators, this research aims to contribute to developing lagging regions and introducing an eco-friendly atmosphere. The concept of sustainable resort development becomes a key to long-term success in the tourism industry [27]. Proper management is crucial to ensuring the sustainability of beach resorts, particularly within the rapidly growing tourism industry context in Southeast Asia. This study provides an overview of efforts made by resorts to maintain efficient operations while balancing economic considerations with environmental and social responsibilities, offering insights into effective strategies that can support long-term sustainability for tourism institutions [28].

Joseph-Ikinako and Success [29] emphasize increased interest in environmentally friendly products and services, indicating a heightened societal awareness of environmental sustainability. This study underscores the importance of integrating sustainability principles into tourism practices, with a particular focus on ecotourism and resort planning at Marang Resort. By investigating strategies implemented by Marang Resort in addressing environmental issues, this study aims to provide valuable insights into sustainable tourism fields.

3. Method

Located in Yogyakarta, Indonesia, the resort is situated on Samas Kuwaru Road, Kaliwungu, Gadingharjo, Bantul, Parangtritis. Geographically, Yogyakarta is a special region located in the southern part of Java Island, Indonesia (**Figure 1**). With its strategic location, Puri Brata Resort & Gallery offers a unique experience for its visitors, which includes interaction with the local natural and cultural environment.

Figure 1. Location map of Puri Brata Resort in Yogyakarta.

In this study, a case study analysis will be employed as the primary method to evaluate the design of Puri Brata Resort & Gallery, with a focus on the aspects of environmental aesthetics and sustainability. The research will begin with a comprehensive exploration of the resort's design concept, which includes materials, energy usage, and synergy with the local ecology. Data collection will be carried out through direct observations, measurements, and evaluations of related documents, such as floor plans. The gathered data will be examined to identify practices that support sustainability and the integration of environmental aesthetic elements in the design. The findings from this analysis are expected to reveal the effectiveness and efficiency of the implemented sustainability strategies, as well as their contribution to the aesthetics and comfort of visitors. This methodological approach is designed to provide a deep understanding not only of the technical aspects of sustainability but also of the aesthetic values produced by sustainable design.

4. Results and discussion

Based on the data collection and analysis conducted, several significant findings were discovered as follows:

1) Sustainability in Architecture

Puri Brata Resort & Gallery actively utilizes recycled materials in its construction and furniture. For instance, reclaimed wood is used to create furniture and decorations (**Figure 2**), while eco-friendly building materials like bamboo, which has a rapid regeneration capability, are also employed.

Figure 2. Old wood material.

Puri Brata Resort & Gallery has successfully utilized recycled materials for approximately 60% of the total materials used in the construction of their buildings and furniture. This demonstrates a strong commitment to sustainability and efficient use of resources (**Table 1**).

Table 1. Recycled materials usage.

Building construction	Total materials used: 100 units Recycled materials used: 60 units
Furniture	Total materials used: 50 units Recycled materials used: 30 units

Puri Brata Resort & Gallery implements ecological principles in its building design by creating active green open spaces. The layout of the building masses is arranged to provide abundant opportunities for planting green vegetation, both around the buildings and within open spaces. This provides benefits such as improved air quality and temperature control and creates a healthy environmental quality for residents and resort guests.

Through direct measurements and surveys of residents and guests, research shows that the active green spaces in Puri Brata Resort have a positive impact on air quality and temperature control. Airborne particles (PM2.5) and CO_2 concentration are lower in green spaces compared to non-green areas. The average daytime and nighttime temperatures are also lower in green spaces. Survey results indicate higher levels of satisfaction regarding air quality and environmental temperature in green spaces. Thus, it can be concluded that active green spaces contribute positively to air quality, temperature control, and creating a healthy environment for residents and guests of the resort (**Table 2**).

Table 2. The effect of active green space on air quality, temperature control, and environmental health.

1	**Air quality**	**Green space**	**Non-green space**
	Particulate matter (PM 2.5)	12 μg/m³	20 μg/m³
	CO_2 concentration	400 ppm	500 ppm
2	Temperature controller		
	Daytime average temperature	25 ℃	30 ℃
	Nighttime average temperature	20 ℃	23 ℃
3	Environmental health (resident and resort guest survey results)		
	Satisfaction with air quality	85%	65%
	Satisfaction with environmental temperature	80%	60 %

This resort also implements renewable energy systems, such as solar panels, to produce environmentally friendly electricity. Using solar panels as a renewable energy source to generate electricity demonstrates the resort's commitment to utilizing clean and sustainable energy sources, thereby helping to reduce greenhouse gas emissions. The resort can also leverage the abundant solar energy potential at their location, reducing the use of non-renewable energy and lowering operational costs in the long term. The success of this resort in implementing renewable energy systems serves as a positive example for the tourism industry in maintaining environmental sustainability (**Figure 3**).

(a) **(b)**

Figure 3. (a) Solar panels; **(b)** wide openings.

Puri Brata Resort Yogyakarta is committed to implementing the use of renewable energy in its operations, with a primary focus on utilizing solar power. The resort has installed solar panels with a capacity of 30 kilowatts (kW) and has successfully generated 20 kilowatts (kW) of renewable energy. This equates to 25% of the resort's total energy consumption, demonstrating concrete steps towards sustainability and energy efficiency. This effort reflects Puri Brata Resort Yogyakarta's commitment to minimizing environmental impact and contributing to the conservation of nature (**Table 3**).

Table 3. Use of renewable energy.

Type of renewable energy	Solar power
Energy production capacity	30 kilowatts (kW)
Energy consumption from renewable sources	20 kilowatts (kW)
Total energy consumption	80 kilowatts (kW)
Percentage of energy consumption from renewable sources: 25%	

The influence of ventilation design, natural lighting, and electricity usage management can be key factors in achieving energy efficiency in buildings (**Figure 3**). These factors can contribute to realizing green architecture standards for buildings [30]. In Indonesia, there are two regions with significant differences in microclimates. Mountainous regions have cooler climates, while coastal regions have hotter climates. Despite the temperature differences between the hot and cold climates in these tropical areas, there is still a characteristic feature of the tropics marked by abundant sunlight. Both the mountainous regions and the coastal regions experience hot temperatures consistent with the nature of the tropical climate [31].

Puri Brata Resort & Gallery employs a rainwater harvesting and processing system, along with an efficient irrigation system, to minimize water consumption. The Kul-Kul on the upper floor can function as a water tower for the middle floor, which serves as a room or storage area, while the lower floor can be used as a toilet (**Figure 4**). This concept offers attractive benefits, especially in terms of energy savings and water efficiency. By utilizing the height of the upper floor as a water tower, the necessary water flow for watering plants on the lower floor can be managed naturally without the need for additional pumps. Water stored in this tank can flow by gravity to the plants below, providing significant economic and environmental benefits. Additionally, using the upper floor as a room or storage area also allows for more efficient space utilization within a building. Therefore, this concept can be an innovative solution for water needs and space management in a building.

Figure 4. Kul-Kul.

Puri Brata Resort & Gallery has implemented a rainwater collection and processing system in its operations. With a total water consumption of 300 cubic meters per month, the resort has successfully collected and used 90 cubic meters of rainwater. Additionally, the resort also treats and reuses 60 cubic meters of wastewater per month. Therefore, it can be concluded that Puri Brata Resort & Gallery has successfully utilized rainwater and wastewater to meet 50% of their total water needs (**Table 4**), demonstrating a strong commitment to sustainability and resource efficiency.

Table 4. Water use and treatment.

Total water consumption	300 cubic meters per month
Rainwater usage	90 cubic meters per month
Water treatment	60 cubic meters of wastewater treated and reused per month

2) Environmental Aesthetics

The resort is designed with careful consideration of the natural contours and surrounding views. The architecture and layout of the buildings draw inspiration from the local nature, creating a harmonious connection between the structures and their environment (**Figure 5**). The cultural approach based on local wisdom, particularly through the philosophy of Tri Hita Karana, is expected to replace the modern individualistic and materialistic perspective. The cultivation of Tri Hita Karana is anticipated to reduce excessive consumerism, conflicts, and social instability. The goal is to achieve a harmonious life by prioritizing devotion to God, love for the environment, and peaceful coexistence with others [32].

Figure 5. Site plan.

The use of natural materials such as wood and stone creates a harmonious blend with the surrounding environment, fostering a sense of connection and authenticity (**Figure 6**). Additionally, the strategic placement of windows and skylights allows for sufficient natural light to illuminate the rooms, enhancing the overall aesthetics. Attention to these details not only creates a visually pleasing atmosphere but also builds a connection between visitors and the nature outside. The incorporation of artworks and sculptures within the gallery further enhances its visual appeal, providing visitors with a multi-sensory experience. Through these design elements, Puri Brata Resort Gallery successfully creates an aesthetically appealing environment that captivates its visitors.

(a) **(b)**

Figure 6. (a) View of Puri Tumaritis; **(b)** Exterior of Blabag Room.

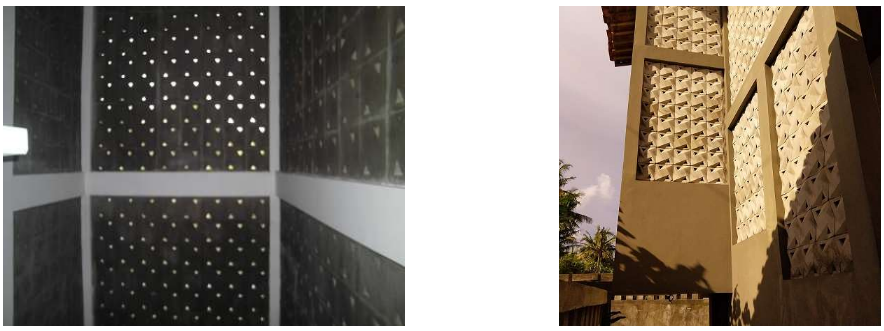


Figure 7. The use of roster in Puri Tumaritis.

The use of roster on the wall at Puri Tumaritis is one of the interesting and unique features. The roster gives a distinctive aesthetic touch to the castle building [33]. Made with intricate and beautiful designs, the roster on the walls of Puri Tumaritis gives the impression of elegance and luxury (**Figure 7**). In addition, the use of roster also has practical benefits. The roster on the wall can function as a good air vent, allowing fresh air flow into the room [34]. This is very important to maintain the air quality inside the castle and provide comfort for the residents. In addition, the roster can also serve as a small window that allows sunlight to enter the room, providing refreshing natural lighting. Thus, the use of roster on the walls of Puri Tumaritis not only provides high aesthetic value, but also provides practical benefits that make it more comfortable and cooler.

The design of Puri Brata Gallery Resort also pays attention to and respects local cultural values. Traditional motifs and ornaments are used in design elements to enrich the visitor experience and create a connection with the local culture (**Figure 8**). This enhances visitor satisfaction levels and provides a profound experience of natural and cultural wealth.

Figure 8. Interior of the pavilion.

The interior of the pendopo is a space specifically designed for people to gather and interact in Puri Brata Resort Gallery. The pendopo is one of the important aspects of traditional Javanese architecture, possessing high historical and cultural value. In this pendopo, visitors can strongly feel the traditional Javanese atmosphere through its distinctive design and decorations. The walls of the pendopo are adorned with beautiful carvings and captivating traditional ornaments. The high roof of the pendopo gives a sense of spaciousness and invites fresh air into the room. Inside this pendopo, there are neatly arranged tables and chairs, creating a comfortable and warm atmosphere. Visitors can sit together, have discussions, or simply enjoy the beauty of the surrounding environment. The interior of the pendopo is also equipped with proper lighting, creating a calm and soothing ambiance. The use of natural colors and wood materials in the pendopo's interior adds a natural impression and brings warmth to every corner of the room. With the interior of this pendopo, Puri Brata Resort Gallery provides a unique experience for its visitors, combining natural beauty with the richness of traditional Javanese culture.

Green design plays a crucial role in resort architecture as it not only enhances the aesthetic appeal of buildings but also promotes sustainability and environmental awareness. In the endeavor to create comfort and visual beauty, it is important to emphasize the value of aesthetic quality. This can be achieved through the visualization of plants by considering visual characteristics such as crown shape, leaf and flower color, flower shape, and plant size within the design concept (**Figure 9**). This emphasis suggests that plant characteristics, such as shape, size, texture, and color, are the most prominent aspects in creating aesthetic value [35]. Integrating green spaces in building design creates a harmonious and symbiotic relationship between nature and architecture. The presence of green spaces not only enhances aesthetic appeal but also contributes to the overall well-being of its inhabitants. Gate design is a work of art that reflects the beauty and grandeur of culture, blending traditional Javanese architectural elements with stunning artistic touches.

(a) **(b)**

Figure 9. (a) Parks and open spaces; **(b)** Entrance gate.

5. Conclusion

Research into the Puri Brata Resort & Gallery in Yogyakarta, Indonesia reveals a thoughtfully designed resort that embodies sustainability, environmental aesthetics, and local cultural values. Utilizing a case study method, this research underscores how the resort integrates eco-friendly practices such as incorporating recycled materials, harnessing renewable energy sources like solar panels, and employing rainwater collection systems. The design conscientiously considers the natural contours of the landscape and the scenic views that surround the area, using materials such as wood and stone to seamlessly blend the resort with its environment. The aesthetic harmony is further enhanced through strategically positioned windows and skylights and the innovative use of rosters on the walls, which lend a distinctive aesthetic quality.

In addition, the interior design of Puri Brata Resort—especially within the pendopo (a Javanese pavilion)—places substantial emphasis on local cultural values. Traditional motifs and ornaments are skillfully incorporated into the design, creating a space intended for gathering and interaction that is rich in Javanese decoration and elevates the guest experience. This approach to green design contributes significantly to both aesthetics and sustainability; green spaces throughout the resort create an integrative connection between nature and architecture while offering a serene and rejuvenating atmosphere for guests.

Moreover, the design of the resort's Gate is particularly noteworthy, combining traditional motifs with modern design elements to create an artistic centerpiece that captivates and leaves a lasting impression on visitors. Though further research is required to assess the tangible impacts of these design choices fully, this preliminary study indicates that Puri Brata Resort & Gallery has effectively produced a design that harmonizes aesthetics with environmental consciousness and cultural respect.

This approach provides visitors with a unique and enriched experience. The success of Puri Brata Resort in these areas illustrates a promising model for combining sustainability, environmental aesthetics, and cultural heritage in architectural design. By aligning architectural practices with ecological preservation and cultural integrity, the resort offers valuable insights into developing a sustainable hospitality and tourism industry that honors the natural environment and local heritage.

Author contributions: Conceptualization, HH and AS; methodology, HH and AS; validation, HH, AS and NAA; formal analysis, HH and AS; investigation HH and NAA; resources, AS and NAA; data curation, AS and NAA; writing—original draft preparation, HH and AA; writing—review and editing, HH; visualization, AA; supervision, HH and AS; project administration, NAA; funding acquisition, HH. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Don DeMarinis. Sustainability Matters to Hotel Guests, Staff and The Environment. Available online: https://www.hospitalitynet.org/opinion/4116655.html (accessed on 2 June 2024).
2. Intergovernmental Panel on Climate Change. Climate information relevant for Tourism. Available online: https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Sectoral_Fact_Sheet_Tourism.pdf (accessed on 2 June 2024).
3. WWF. WWF and Greenview Unveil Methodology to Measure Waste Across Hotel Chains. Available online: https://www.worldwildlife.org/press-releases/wwf-and-greenview-unveil-methodology-to-measure-waste-across-hotel-chains (accessed on 2 June 2024).
4. Antonova N, Ruiz-Rosa I, Mendoza-Jimenez J. Water Resource Management in Hotels Using a Sustainable Balanced Scorecard. Sustainability. 2022; 14(13): 8171. doi: 10.3390/su14138171
5. Sari Kalh, Sholeh, MSR. The Development of Biomorphic Architecture and its Integration with Green Architecture Principles. Semsina. 2022; 3(2): 184-190. doi: 10.36040/semsina.v3i2.5104
6. Termal K, Penghematan DAN, Teori E. Realisation in Architectural Design. Available online: https://www.youtube.com/watch?v=jSKnD-d7Js8, 20 April 2024 (accessed on 13 March 2024).
7. Nugroho NF, Afgani JJ. Study of Bioclimatic Architecture Concept in Resort Hotel Building (Hainan Blue Bay Westin Case Study). Purwarupa Jurnal Arsitektur. 2023; 7(1): 21. doi: 10.24853/purwarupa.7.1.21-26
8. Nazarudin R, Anisa A. Study of the Concept of Ecological Architecture in the Alam Asri Resort Hotel Area. Rustic. 2020; 1(1): 11-21. doi: 10.32546/rustic.v1i1.885
9. Anisa A. Study of Ecological Architecture Concept in Resort Area Case Study: Ayer Island Resort and Cottages. JAUR (Journal of Architecture and Urbanism Research). 2020; 3(2): 129-138. doi: 10.31289/jaur.v3i2.3413
10. Schiano-Phan R, Soares Gonçalves JC. Sustainability in Architectural Education—Editorial. Sustainability. 2022; 14(17): 10640. doi: 10.3390/su141710640
11. Schroeder T. Giving Meaning to the Concept of Sustainability in Architectural Design Practices: Setting Out the Analytical Framework of Translation. Sustainability. 2018; 10(6): 1710. doi: 10.3390/su10061710
12. Kumar SA, Yadav M. Sustainability in Architecture: Dynamic Buildings, “The Future of India.” International Journal of Engineering Research & Technology. 2020; 1508-1511.
13. Yin W. The Importance of architecture in shaping our built environment. International Journal of Advancements in Technology. 2023; 14: 1-2.
14. Ismaeel WSE. The Dynamics of Sustainable Material Selection for Green-Certified Projects. Buildings. 2023; 13(8): 2077. doi: 10.3390/buildings13082077

15. Alkasar BE, Yahya HA. A Comparative Analysis of Design Criteria Influencing Building Material Selection Across Different Architectural Contexts. International Journal of Sustainable Development and Planning. 2023; 18(10): 3117-3124. doi: 10.18280/ijsdp.181014
16. Li S. Sustainable Material Selection in Architectural Design. Atlantis Press SARL; 2024. pp. 4-10.
17. Daugelaite A, Grazuleviciute-Vileniske I. The Relationship between Ethics and Aesthetics in Sustainable Architecture of the Baltic Sea Region. Sustainability. 2021; 13(4): 2259. doi: 10.3390/su13042259
18. Celadyn W, Celadyn M. Architectural Detail in Sustainable Architecture: Formal and Aesthetic Connotations. Sustainability. 2024; 16(11): 4502. doi: 10.3390/su16114502
19. Wahba SMED. Friendly and Beautiful: Environmental Aesthetics in Twenty-First-Century Architecture. Nexus Network Journal. 2010; 12(3): 459-469. doi: 10.1007/s00004-010-0045-1
20. Daugelaite A, Dogan HA, Grazuleviciute-Vileniske I. Characterizing sustainability aesthetics of buildings and environments: methodological frame and pilot application to the hybrid environments. Landscape Architecture and Art. 2021; 19(19): 61-72. doi: 10.22616/j.landarchart.2021.19.06
21. Hegazy I, Seddik W, Ibrahim H. The living building: integrating the built environment with nature evaluating the Bibliotheca of Alexandria according to the challenge imperatives. International Journal of Low-Carbon Technologies. 2017; 12(3): 244-255. doi: 10.1093/ijlct/ctx003
22. Fei T, Liu Y, Guo J. Visual Integration Relationship between Buildings and the Natural Environment Based on Eye Movement. Buildings. 2022; 12(7): 930. doi: 10.3390/buildings12070930
23. Manalo G lyn M, Afable FM. Implementation of Green Tourism Practices in the Hotels and Resorts of White Beach Puerto Galera. American Journal of Tourism and Hospitality. 2023; 1(1): 27-34. doi: 10.54536/ajth.v1i1.1769
24. Harindra Syam F, Wisdianti D, Sajar S. Study of Sustainable Architecture Concepts. International Journal of Research and Review. 2023; 10(4): 419-424. doi: 10.52403/ijrr.20230450
25. Rana S. Sustainability in Business: Some Research Perspectives. FIIB Business Review. 2019; 8(2): 77-78. doi: 10.1177/2319714519854232
26. El-Barmelgy H, Ibrahim A. Eco-efficient resort planning and design. A practical case study of Marina el-Alamien. Journal of Urban Research. 2014; 13(1): 113-130. doi: 10.21608/jur.2014.92879
27. Pawar M, Patil A, Shelar A, et al. Analysis and design of sustainable resort. VIVA-Tech International Journal for Research and Innovatio. 2021; 1: 38-43.
28. Mustapha M, Wahidin Awang K. Sustainability of a beach resort: A case study. International Journal of Engineering & Technology. 2018; 7(2.29): 210. doi: 10.14419/ijet.v7i2.29.13319
29. Joseph-Ikinako. Sustainable Eco tourism: A case study of Marang resort. Global Scientific Journal. 2021; 9(4):165-79.
30. Niza A, Setiyani A, Sekarkinasih D, et al. Influence of openings for energy efficiency in buildings and green areas Case. Study of Majapahit Eco-Resort in Mojokerto. 2020; 3(2): 507-518.
31. Hermawan H, Fikri MA. Kinerja Thermal Performance of Timber Walled, Tile Roofed and Ground Floored Houses in the Warm Tropics. Jurnal Ilmiah Arsitektur. 2020; 10(2): 54-60. doi: 10.32699/jiars.v10i2.1619
32. Ismulyadi CB. The Hybridity of Puri Brata Pilgrimage. Rhetoric: Journal of Humanities. 2018; 5(1): 395. doi: 10.24071/ret.v5i1.1521
33. Fasbira Mustofa A, Yus Fauziah I. Effect of roster pattern on the effectiveness of natural lighting and visual comfort of the building (Case Study: Asy Syams Kulon Progo Mosque). Curating the Past to Build Architectural Business. 2022; 334-344.
34. Muhsin A, Nabila A, Purnama A. Influence of Roster Design and Pattern on Simulated Natural Airing of Building Facades. J Reka Karsa. 2022; X(3): 1-7.
35. Lestari G, Gunawan A. The influence of tree canopy shape on the aesthetic quality of streetscapes. J Lanskap Indones. 2010; 2(1): 30-35.

Building Engineering 2024, 2(2), 1381.
https://doi.org/10.59400/be.v2i2.1381

Article

Sealing of roof penetrations during building construction

Scott. A. Lowe

Civil & Environmental Engineering Department, Manhattan College, Bronx, NY 10471, USA; Scott.Lowe@manhattan.edu

CITATION

Lowe SA. Sealing of roof penetrations during building construction. Building Engineering. 2024; 2(2): 1381. https://doi.org/10.59400/be.v2i2.1381

ARTICLE INFO

Received: 15 May 2024
Accepted: 20 July 2024
Available online: 3 August 2024

Abstract: For new building construction, roofs typically have a large number of penetrations that are blocked out before the roof deck is poured. After the roof is poured, these penetrations need to be sealed temporarily to prevent rainwater entering the building. Unfortunately, it is all too common that the ad-hoc approach to sealing these openings results in penetrations left open to the elements. This results in water pouring into the building every time it rains. This paper shows examples of unsealed roof penetrations and of the subsequent damage caused. The penetrations relate to the work of several different trades, who may not place any priority on this issue. It is therefore suggested that this is a problem that the construction management team has to take charge of. At the very least, the roof should be inspected before impending rain events.

Keywords: safety; management; damage; conditions; decking

1. Introduction

During building construction, there are many temporary measures that must be undertaken to ensure both a safe and productive work environment [1,2]. One of the major safety risks on a worksite is wet conditions [3,4]. This increases the risks of slips and falls [5,6]. There is also an increased electrical hazard, as extension cords can end up sitting in standing water [7,8]. The risks are exacerbated when one finds water in unexpected areas, i.e., indoors, for example.

One of the more annoying conditions that are consistently observed on new building projects is seeing every floor of the building wet, even though the roof slab has been poured. The source of the problem is obvious if one visits the roof—roof penetrations that have not been sealed. As this is a construction process issue, no guidance will be found in the building codes like the International Code Council's (ICC) International Building Code [9].

Why this occurs is less a physical issue than a management issue. Temporarily sealing roof penetrations is not technically difficult. It is more a question of who will take responsibility. The penetrations will belong to many of the trades, from plumbers to electricians to HVAC contractors. Often penetrations are initially sealed, but then the seals are breached as pipes are centered in the block-out sleeves, for example. In this author's experience, once the initial seals are breached, very few people spend the time to reseal the area. This is now more complicated as it involves sealing a gap between the pipe and sleeve, with various centering wedges or a riser clamp also in place.

So obviously, ad hoc responsibility for roof penetrations is not a successful system. The consequences can be expensive—damages can quickly mount into tens of thousands of dollars, especially considering how many times it will rain over the course of the project. One slip and fall injury on a wet floor, or electrical mishap due to power cords sitting in water, will cost much more [10–14]. So, someone must be given overall responsibility for maintaining the roof integrity, and that must likely come from the construction management team.

Whoever accepts the responsibility must be aware of the length and frequency of such a commitment. The time span between a roof being poured and the last penetration being finalized will typically be months, not weeks, for most projects. At any time, someone may unseal a penetration to do some work and leave it unsealed. So frequent inspections will be required to catch this. At the very least, a roof inspection before a projected rain event is required.

The remainder of this paper is broken into two sections. The first details typical roof penetrations and sealing issues. The second section shows examples of the damage caused by failing to real roof penetrations adequately.

2. Examples of unsealed roof penetrations

Roofs have a myriad of penetrations that are typically blocked out before the roof deck is poured. These include the roof drains themselves, plumbing waste system vents (soil stacks), vents from kitchens, vents from boilers, electrical conduits, Heating, Ventilation and Air Conditioning (HVAC) shafts, and even water pipes. Ideally, these would each be sealed temporarily, but comprehensively, to prevent rain pouring through to the floors below.

Figure 1 shows a vent pipe sitting within the sleeve that penetrated the roof. The tape remnants indicate that the sleeve was initially sealed, but whoever positioned the vent did not bother to reseal around the pipe perimeter. **Figure 2** shows a soil stack vent where again the temporary seal on the sleeve was removed but not replaced when the pipe was centered. This pipe was left like this for weeks. **Figure 3** shows four small penetrations, maybe for electrical cabling, that were never sealed.

Figure 1. Vent pipe positioned in a roof sleeve. The pipe is not sealed nor is the gap between the sleeve and the pipe.

Figure 2. Temporary sleeve seal was breached by the pipe and not resealed.

Figure 3. These four penetrations were never sealed.

Large penetrations cause large problems. **Figure 4** shows one method of dealing with a large penetration. The metal decking has been placed, but the concrete has been blocked out. This will work as long as the opening does not fill up with too much water—at which point the water will flow through any seams in the steel decking.

Figure 4. An alternative to leaving a large penetration is to place the metal decking but not pour over it.

Figure 5 is indicative of the lax approach to temporary sealing. This sleeve seal was opened at some point and never resealed. **Figure 6** shows a sheet of plywood that was used to seal a large duct penetration. The gaps along one side are obvious. It is also clear that plywood sitting on concrete will never create a water tight seal; it just gives the illusion of being a seal.

Figure 5. At some point the seal on this sleeve was opened but no one closed it back up.

Figure 6. This large duct penetration was covered by plywood but the gaps are obvious.

3. Examples of the damage caused

Figure 7a shows an auditorium floor that is recessed into the floor slab. As it began to rain, water immediately started to enter the auditorium area. **Figure 7b** also shows the auditorium an hour later, full of standing water. Notice how workers had to move bags of mortar off the floor and place them on some steel masonry reinforcement to keep them from being ruined.

(a) **(b)**

Figure 7. (a) As it started raining water immediately began to enter this sunken auditorium area; **(b)** An hour later the floor had standing water.

Figure 8. This was on the 1st floor of a six-story building. This drywall ultimately had to be replaced.

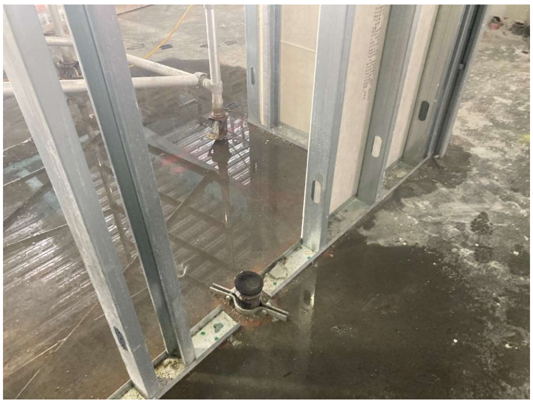


Figure 9. Water starting to spread to an area where drywall had just been installed—this also had to be replaced.

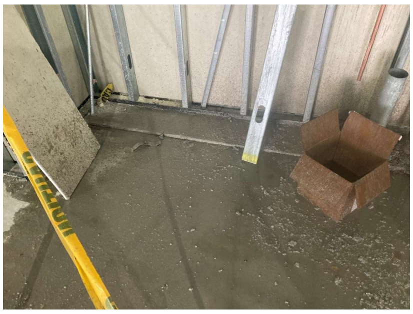


Figure 10. This was the day after the rain. The floors remained wet for another two days. Notice the caution tape and the wet drywall.

In steel-frame buildings, spray-on fireproofing is commonly used. This fireproofing does not interact well with water and easily sloughs off when exposed to almost any water. **Figures 11–14** show examples of this.

Figure 11. This fireproofing on the beam had already been patched (the light areas). It is in the process of sloughing off again as water leaks onto it – notice the exposed steel.

Figure 12. Water penetrating the fireproofing as it started to rain.

Figure 13. Fireproofing washed away as water ran down the inside of a precast wall panel.

Figure 14. This is fireproofing on the floor that had sloughed off a column.

Apart from damage, there are also the safety aspects. This includes power cords running across wet floors and workers carrying loads walking over wet floors.

Last, but not least, is the huge annoyance and inefficiency of having everyone working inside a topped-off building walking around in water. Any material that is staged and can be damaged by the water has to be restaged to remain dry. If that particular contractor is not on site that day, they may return to see their staged material ruined. Even if the leaks limit the water to certain areas of a particular floor, it will surely be trekked throughout the entire floor. The day after the rain, workers will have to be tasked to dry the floors and sweep up the mess.

Figures 15 and **16** give an indication of the poor work conditions roof leaks can cause.

Figure 15. Poor working conditions due to wet floors. This is several floors below roof level.

Figure 16. This bucket was placed under a leak. Eventually it filled up and overflowed.

Figure 17. This building has precast concrete wall panels. Water is running off the floor slab and falling down between the gap to lower floors.

Figure 17 shows a building with precast concrete wall panels as the façade. There is always a gap between the end of the floor slab and the wall panels. The figure shows water flowing to the edge of the slab and falling down between the gap to the floors below. This caused the damage to the sprayed-on fireproofing shown previously in **Figure 13**.

4. Conclusions

In new building construction, roof leakage from failing to provide adequate temporary sealing for roof penetrations is a common problem. The damage caused by the leaks can be extensive. Drywall is extremely vulnerable to water damage and will need to be replaced if it gets wet. Sprayed-on fireproofing easily sloughs off in the presence of water. The risk of slip and fall accidents and electrical mishaps is also present. Staged material can also be damaged, e.g., mortar bags sitting on the floor that get wet.

As roof penetrations belong to various trades, it means that overall responsibility must likely fall on the construction management team. The timeframe from when the roof is initially poured to when the last penetration is finalized is likely to be months—so this is not a short-term commitment. Sealed penetrations can be unsealed at any time as work progresses and will often not be resealed. This means frequent inspections. At the very least, the roof should be inspected before impending rain events.

Conflict of interest: The author has no conflict of interest.

References

1. Mattila M, Rantanen E, Hyttinen M. The quality of work environment, supervision and safety in building construction. Safety Science. 1994; 17(4): 257-268. doi: 10.1016/0925-7535(94)90027-2
2. Jaselskis EJ, Anderson SD, Russell JS. Strategies for achieving excellence in construction safety performance. Journal of construction engineering and management. 1996; 122(1): 61-70. doi: 10.1061/(ASCE)0733-9364(1996)122:1(61)
3. Lipscomb HJ, Glazner JE, Bondy J, et al. Injuries from slips and trips in construction. Applied Ergonomics. 2006; 37(3): 267-274. doi: 10.1016/j.apergo.2005.07.008
4. Sanni-Anibire MO, Mahmoud AS, Hassanain MA, et al. A risk assessment approach for enhancing construction safety performance. Safety Science. 2020; 121: 15-29. doi: 10.1016/j.ssci.2019.08.044
5. Haslam RA, Hide SA, Gibb AG, et al. Contributing factors in construction accidents. Applied ergonomics. 2005; 36(4): 401-415. doi: 10.1016/j.apergo.2004.12.002
6. Chang WR, Leclercq S, Lockhart TE, et al. State of science: Occupational slips, trips and falls on the same level. Ergonomics. 2016; 59(7): 1-23. doi: 10.1080/00140139.2016.1157214
7. Chi CF, Yang CC, Chen ZL. In-depth accident analysis of electrical fatalities in the construction industry. International Journal of Industrial Ergonomics. 2009; 39(4): 635-644. doi: 10.1016/j.ergon.2007.12.003
8. Zhao D, McCoy AP, Kleiner BM, et al. Control measures of electrical hazards: An analysis of construction industry. Safety Science. 2015; 77: 143-151. doi: 10.1016/j.ssci.2015.04.001.
9. International Code Council. 2021 International Building Code. International Code Council; 2021.
10. Oswald D, Ahiaga-Dagbui DD, Sherratt F, et al. An industry structured for unsafety? An exploration of the cost-safety conundrum in construction project delivery. Safety Science. 2020; 122: 104535. doi: 10.1016/j.ssci.2019.104535
11. Haupt TC, Pillay K. Investigating the true costs of construction accidents. Journal of Engineering, Design and Technology. 2016; 14(2): 373-419. doi: 10.1108/jedt-07-2014-0041
12. Allison RW, Hon CK, Xia B. Construction accidents in Australia: Evaluating the true costs. Safety science. 2019; 120: 886-896. doi: 10.1016/j.ssci.2019.07.037
13. Kim JM, Ha KC, Ahn S, et al. Quantifying the Third-Party Loss in Building Construction Sites Utilizing Claims Payouts: A Case Study in South Korea. Sustainability. 2020; 12(23): 10153. doi: 10.3390/su122310153
14. Yang L, Branscum A, Smit E, et al. Work-related injuries and illnesses and their association with hour of work: Analysis of the Oregon construction industry in the US using workers' compensation accepted disabling claims, 2007-2013. Journal of Occupational Health. 2020; 62(1). doi: 10.1002/1348-9585.12118

Building Engineering. 2024; 2(2): 1451.
https://doi.org/10.59400/be.v2i2.1451

Article

Fighting for collusive bidding in the construction industry: A text mining-enabled approach

Xiaowei Wang[1,*], Keda Chen[2], Yuqing Zhang[2]

[1] Department of Civil and Environmental Engineering, University of Michigan, MI 48109, USA
[2] School of Management Science and Real Estate, Chongqing University, Chongqing 400045, China
*** Corresponding author:** Xiaowei Wang, xiaowei.xw.wang@outlook.com

CITATION

Wang X, Chen K, Zhang Y. Fighting for collusive bidding in the construction industry: A text mining-enabled approach. Building Engineering. 2024; 2(2): 1451. https://doi.org/10.59400/be.v2i2.1451

ARTICLE INFO

Received: 17 June 2024
Accepted: 11 September 2024
Available online: 25 September 2024

Abstract: Policy measures are crucial for regulating collusive bidding and are integral to effective governance. However, current research lacks a comparative exploration of strategies to combat collusive bidding through policy. Therefore, this study aims to identify more effective countermeasures by examining policy variations between regions with low and high incidences of collusive bidding. Using Latent Dirichlet Allocation (LDA) topic modeling, the study extracts key themes from these policies, while qualitative analysis highlights differences in approaches. It underscores that integrating electronic and information technology into bidding systems significantly reduces collusive practices. While increasing penalties can deter collusive bidding, achieving desired impacts requires thorough investigation and vigilant oversight. Additionally, strengthening external supervision enhances control over such activities. This study identifies critical governance strategies for addressing collusive bidding and advocates further research into more effective methods within the construction sector.

Keywords: collusive bidding; policy; government; text mining; comparation

1. Introduction

Collusive bidding is widely considered the most socially detrimental form of anticompetitive practice [1,2]. Construction projects obtained through collusive bidding often suffer from mismanagement and poor quality, leading to serious safety hazards and posing a threat to public security [3]. For instance, the collapse of a cooling tower during the construction of Phase 3 of the Fengcheng Power Plant in Yichun City, China, resulted in more than 70 fatalities; subsequent investigations revealed that this tragedy was caused by collusive bidding [4]. Similarly, the widely discussed "problematic road" project in Fuzhou City, China, with a total cost of 813 million RMB, experienced significant road surface subsidence of 30–50 centimeters and a qualified pile foundation rate of 0, both attributable to widespread collusive bidding [5]. Beyond these bad repercussions, collusive bidding also seriously disrupts the order of the construction market, inefficient allocation of market resources, and harms social and economic interests [6–8].

Policy measures serve as the foundation for governing collusive bidding and constitute an essential aspect of government governance [9]. Implementing well-thought-out and reasonable policy measures, along with establishing a comprehensive policy framework, can effectively deter collusion. Many researchers, therefore, have been focusing on how to fight for collusive bidding in the construction industry from the perspective of policy measures [6]. For instance, the researchers explored the influence of external environments on bidders' collusive behaviors and aimed to formulate the specific policies in different external environments, thereby enhancing the governance effectiveness of collusive bidding [10–12]. Some scholars discussed the punitive measures [13–15]. This is because punitive measures are the common tool used by governments to warn bidders to respect fair competition [16]. However, the current research has not extensively explored the measures for countering collusive bidding from a policy comparison perspective.

Policy comparison can offer in-depth analysis and insights, aiding decision-makers in gaining a better understanding of the impacts and outcomes of different policy measures [17]. In previous research, policy comparison has been frequently used to analyze different countries/regions to help the decision-makers develop more effective policy measures [11]. For example, Long et al. [11] compared seven selected national/regional drone regulations to identify the applicability of implementing the existing regulations in construction and aim to develop a multi-dimensional regulatory framework for using drones in the construction industry. Thus, to fill this gap, the study aims to develop more effective countermeasures against collusive bidding by examining the differences in policy measures with policy comparison.

In China, collusive bidding in the region of central China is higher than in the region of eastern China [10]. This is because eastern China, located in the socio-economically developed region, has more sound policies and bidding systems than the region of central China [11]. By comparing the policies of these contrasting regions, it becomes possible to discern the distinctions in policy approaches between areas characterized by low and high collusive bidding tendencies. Thus, this research compares the policies related to bid violations implemented in regions with low incidences of collusive bidding to those in regions with high incidences of collusive bidding. This analysis offers valuable insights into devising more efficacious strategies for curtailing collusive behaviors among bidders in regions where such practices are more prevalent.

2. Literature review

2.1. Collusive bidding in construction

Competition in the construction industry is known for its high levels of uncertainty, which leads to collusive bidding [11,18]. Collusive bidding refers to the behavior where two or more participants in the bidding process form an alliance to gain undue advantages [19]. They engage in irregular practices to control or influence the bidding outcome, causing financial losses to other participants. The establishment of collusive bidding requires three fundamental conditions: the presence of two or more participating entities, the ability to form subcontracts to distribute collusive gains, and the existence of negative externalities. Collusive bidding is mainly divided into three major categories: horizontal collusion, vertical collusion, and mixed collusion, as shown in **Figure 1**. The significant distinction among the three collusion forms lies in the involvement of different parties. Collusion between bidders is referred to as horizontal collusion; collusion between bidders and other stakeholders (excluding other bidders) is known as vertical collusion; and collusion involving bidders, other stakeholders, and other bidders is termed mixed collusion. Existing literature indicates that horizontal collusion is the most easily formed and also the most severe form of collusion in the construction industry [7].

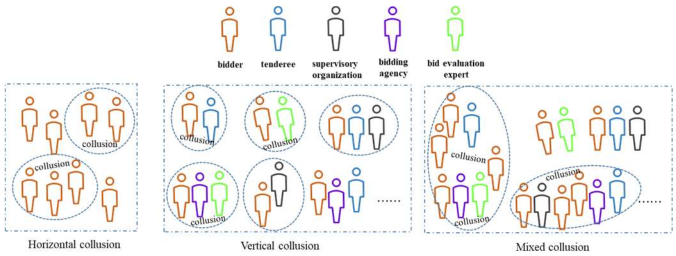


Figure 1. Types of collusive bidding.

Shi et al. [7] asserted that the primary factors encouraging collusive behaviors in bidding are the excessive competition and low profit margins experienced by contractors in the construction industry, which make them prone to engaging in collusive practices in markets with few competitors [20]. Moreover, larger firms tend to submit higher bids to seek higher profits [18], and their substantial market shares enable them to implement collusion strategies to maintain their competitive advantage. Bolotova et al. [21] verified the aforementioned claims and suggested that collusive behaviors in engineering are more likely to occur if the external environment incentivizes them to obtain higher profits. Dorée [22] exemplified the construction industry in the Netherlands to demonstrate that contractor greed is the primary driver of collusive behaviors in bidding. Moreover, businesses within the same region have more opportunities for business interactions, leading them to engage in private communications without arousing suspicion [23].

Some scholars present different perspectives on this matter. Ratshisusu [24] suggests that project scale can also lead to collusive behaviors in bidding. Morselli and Ouellet [18] argue that the composition of the construction market, consisting of a few large enterprises and a vast majority of small and medium-sized enterprises, is an important factor contributing to collusive bidding. Stigler [25] posits that market conditions, such as the number of competitors, barriers to entry, frequency of interactions, market transparency, demand growth and fluctuations, business cycles, market share distribution, and cost asymmetry, significantly influence the decision to engage in collusive practices. Wang et al. [26] and Oke et al. [27] unanimously agree that the main reason for the occurrence of collusive bidding is the inadequacy of punishment severity and regulatory oversight.

2.2. Measures for fighting collusive bidding

Prevailing research concerning the measures for fighting collusive bidding predominantly focuses on approaches that elevate the costs associated with collusion, diminish collusive gains, and bolster the intensity of oversight and punitive measures [28]. For instance, Allain et al. [29] argue that collusive governance should consider the economic environment and agents' risk preferences. Ratshisusu et al. [24] suggest that the owner's attitude significantly influences collusion among project participants, and different governance approaches should be adopted for various levels of collusion. Some scholars propose increasing the severity of penalties to reduce collusion occurrences [16,27,30,31]. In addition to increasing the punishment severity, Oke et al. [27] recommend encouraging professionals to report suspicious activities and transactions, including collusion, implementing transparent and open procurement procedures for construction projects, and blacklisting professionals and companies found to be engaged in collusive behavior, revoking their registration to improve engineering performance and enhance the image of the construction industry.

Imposing administrative penalties on collusive bidders has been a common tool used by governments to warn bidders to respect fair competition [16,32]. For instance, France fined 21 construction companies 17.3 million euros for engaging in collusion during the bidding process for highway projects [27]. However, the proliferation of collusion cases indicates that the existing administrative penalties are still insufficient to deter collusive behaviors in engineering bidding [16]. Consequently, some scholars have discussed the optimal level of administrative penalties. Allain et al. [29] argue that the rational deterrence range for cartel fines should be significantly higher than the minimum threshold of administrative penalties, which is typically around 60%.

Existing research on collusive bidding monitoring methods primarily focuses on employing statistical methods to analyze the irregularities in bidders' quotations [33]. For example, Ballesteros-Pérez et al. [34] use the distribution of bid prices to detect abnormal collusive bidders. Erfani et.al [35] introduce a data-driven model called the Test of Abnormal Bid (TAB). This model employs Benford's law, a method commonly used for fraud detection in auditing and finance, to quickly identify price irregularities. Chotibhongs and Arditi [33] suggest that owners can refer to historical bidding data and use statistical tests to screen for suspicious collusive bidders. Porter and Zona [36] compared the cost structures of known collusive bidders and non-collusive bidders in highway construction projects and suggested analyzing anomalies in bidding to detect collusion. These studies indicate that collusive bidders' quotations differ from those of normal bidders, and this dissimilarity can be analyzed to identify collusive participants. In addition, other scholars have proposed alternative collusion monitoring methods. Padhi and Mohapatra [37] developed a control chart that directly detects colluders after bid opening, which was validated using engineering projects in India. Subsequently, they proposed controlling collusion during the procurement process by adjusting auction parameters [38].

3. Methodology

3.1. Policy text collection

According to the research of Wang et al. [1], Wang et al. [6], and China judgment online [11], collusive bidding cases are relatively less frequent in the eastern regions of China, specifically in Beijing, Shanghai, and Guangdong. In contrast, the central regions of China, particularly the provinces of Hunan, Hubei, and Jiangxi, have the highest number of collusive bidding cases. Therefore, this research selects Beijing, Shanghai, and Guangdong in the eastern regions as the comparative provinces/cities for the study. It compares the policy measures implemented in these three provinces/cities regarding bid-related illegal and irregular practices with those of Hunan, Hubei, and Jiangxi. The goal is to identify differences in policy measures and propose effective governance strategies to improve collusive bidding practices in China.

Peking University Legal Information Database (PULID), founded in 1985, is currently the most authoritative legal regulation information retrieval system in China [39]. Based on the selected provinces/cities, the research utilizes the official websites of local governments and the search function of the PULID; keywords such as "bidding," "collusion," "bid-rigging," and others were used to collect and compile relevant policy documents from the selected provinces/cities. A total of 36 policy documents were collected from Beijing, Shanghai, and Guangdong, while 16 policy documents were collected from Hunan, Hubei, and Jiangxi. The textual content of these policy documents serves as the primary material for policy analysis in this research.

3.2. LDA topic text mining

Latent Dirichlet Allocation (LDA) topic model is currently a hot topic in the field of text mining [40]. It is applicable for extracting topics and keywords from large-scale unlabeled documents and achieving document clustering [41]. The LDA model effectively handles dimensionality reduction of text content, integrating high-dimensional words into low-dimensional topics, thereby reducing the interference of noisy words, and facilitating the capture of key information and efficient classification of texts. This method is particularly suitable for mining topics in policy texts. Therefore, the research selects the LDA topic model as the primary method for policy text mining in this study.

The LDA topic model is a three-layer Bayesian probabilistic graph, consisting of document, topic, and word layers. The model can be applied to a single document or multiple documents, and it generates one or multiple topics and their corresponding words, following a multinomial distribution. Each topic is associated with a probability distribution over the words that describe the topic. LDA model structure diagram, as shown in **Figure 2**. In **Figure 2**, α represents the parameter of the Dirichlet prior on the per-document topic distributions. It controls the distribution of topics in each document. θ_m represents the topic distribution for document m. It is a vector that specifies the proportion of each topic within the document. $Z_{m,n}$ represents the topic for the nth word in the m_{th} document. It indicates which topic the word is associated with in the context of the document. $\omega_{m,n}$ represents the nth word in the m_{th} document. φ_k represents the word distribution for topic k. It is a vector that specifies the proportion of each word within the topic. β represents the parameter of the Dirichlet prior on the per-topic word distributions. It controls the distribution of words in each topic. The detailed process is as follows: (1) Sampling from the Dirichlet distribution α to generate the subject distribution θ_i of document i; (2) Sampling from the multinomial distribution θ_i of the topic to generate the subject $Z_{i,j}$ of the j-th word of document i; (3) Sampling from the Dirichlet distribution β to generate the word distribution $\Phi_{Zi,j}$ corresponding to the topic $Z_{i,j}$; (4) Sampling from the multinomial distribution of words $\Phi_{Zi,j}$ finally generates words $\omega_{i,j}$.

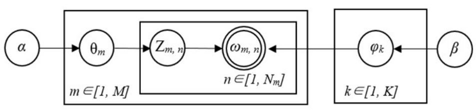


Figure 2. The basic logic of LDA.

In the training document set M, the joint distribution of known variables and hidden variables existing in the LDA model is as follows.

$$p(w_i, Z_i, \theta_i, \overline{\omega}|\alpha, \beta) = \prod_{i=1}^{N} p(w_{i,j}|\overline{\omega}_{Zij})p(Z_{i,j}|\theta_i) \cdot p(\theta_i|\alpha)\, p(\overline{\omega}|\beta) \tag{1}$$

In Equation (1), N represents the total number of words in a document, and the maximum likelihood function estimation of document word distribution is:

$$P(w_i|\alpha, \beta) = \int_{\theta_i} \int_{\varphi} \sum_{Z_i} p(w_i, Z_i, \theta_i, \overline{\omega}|\alpha, \beta) \tag{2}$$

In the training process of the document set, the number of topics needs to be determined in advance, and the entire document set is used as the input content.

The most crucial step in LDA topic modeling is hyperparameter tuning, specifically the selection and determination of the number of topics K. The approach used to set the number of topics involves visualizing the results of the topic modeling in a two-dimensional space and observing the distances between topics and the degree of overlap. The LDAvis tool enables users to interactively adjust and identify the most useful words that represent specific topics, thereby improving the readability and distinctiveness of the topics. In this study, this method is employed to extract topic-representative words using the relevance formula:

$$r(w, k|\lambda) = \lambda\, log(\emptyset_{kw}) + (1-\lambda)log\left(\frac{\emptyset_{kw}}{p_w}\right) \tag{3}$$

In the formula, *k* represents a specific topic, *w* represents a word, *r* represents the degree of association between the word and the topic, $\emptyset_{kw}$ represents the probability of word *w* in topic *k*, and λ is a variable parameter with a value between 0 and 1. When λ approaches 0, it indicates that topic-representative words have exclusivity (i.e., words that are more unique and specific to the topic have stronger relevance to that topic). When λ approaches 1, it means that words that appear more frequently in the topic can better represent that topic. By specifying a value for λ, the relevance between word *w* and topic *k*, denoted as $r(w, k|\lambda)$, can be adjusted.

3.3. Topic-generating procedure

In this study, most of the policy texts are full policy documents, containing numerous specialized terms and adhering to standard and continuous semantic expressions. To ensure that the final topics align with the research objectives, text preprocessing is necessary before generating the topics. The preprocessing steps mainly include tokenization and stop word filtering. The first task in file preprocessing is tokenization, and the accuracy of tokenization directly affects the quality of subsequent topic classification. Thus, the study uses the "jieba" tool for tokenization. From the tokenization results, it is evident that certain words such as "this regulation" and "this province" do not carry significant meaning in the policies. Hence, it is necessary to filter out stop words to reduce noise in the corpus. In Chinese text, stop words typically include punctuation marks, insignificant prepositions, interjections, etc. Additionally, in specialized research domains, certain words may have high frequencies but little actual significance. For instance, there might be an abundance of terms like "bidding and tendering", "bidding", and "tendering" in the text, which are irrelevant to the policy analysis conducted in this research. Thus, the study employs the stop word filtering feature of the "jieba" tool. After text preprocessing, this study repeatedly adjusted the visualization results and underwent 50 rounds of iteration through multiple clustering processes to obtain the topic identification results related to collusive practices in collected policies. By setting the window and adjusting the λ parameter, the relevance of vocabulary to each topic was enhanced, ensuring a more descriptive representation of the respective themes. In this example, after multiple experiments, both texts' topic selection λ parameter was set to 0.4. The LDA topic model employed high-frequency keywords to describe the topics, and to ensure comprehensive topic descriptions, this study set the number of output keywords per topic to 30.

4. Results

The results of topic text mining for regions with fewer collusive practices in policy texts are shown in **Figure 3**, while the results for regions with higher collusive practices are presented in **Figure 4**. On the left side of both figures, the topic distance maps for the two contrasting texts are displayed. The LDAvis tool visually represents the distances between different topics in a two-dimensional vector space. The size of each circle represents the number of texts included in the corresponding topic. In the two-dimensional vector space, the seven topics show distinct differences and minimal overlap. The central positions of topics 1 to 7 are widely scattered and evenly distributed. This data result indicates that the designated categorization of the seven topics is acceptable. Among the seven topics in **Figure 3**, topic 1 has the highest text distribution, while topics 2, 3, 4, 5, and 6 exhibit relatively similar text quantities, and topic 7 has the lowest text distribution. In **Figure 4**, topics 1 and 2 have the highest text distribution, topics 3, 4, 5, and 6 have relatively similar text quantities, and topic 7 has the lowest text distribution.

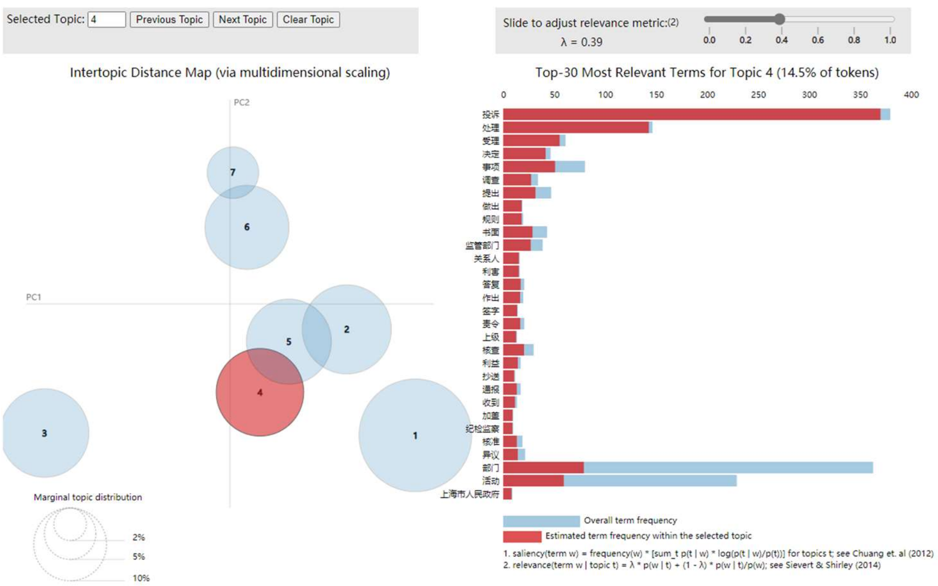


Figure 3. The inter-topic distance map and top-30 most relevant terms for topic 4 in the region of low collusive bidding.

Note: the Chinese in the image corresponds to Topic 4 in **Table 1**.

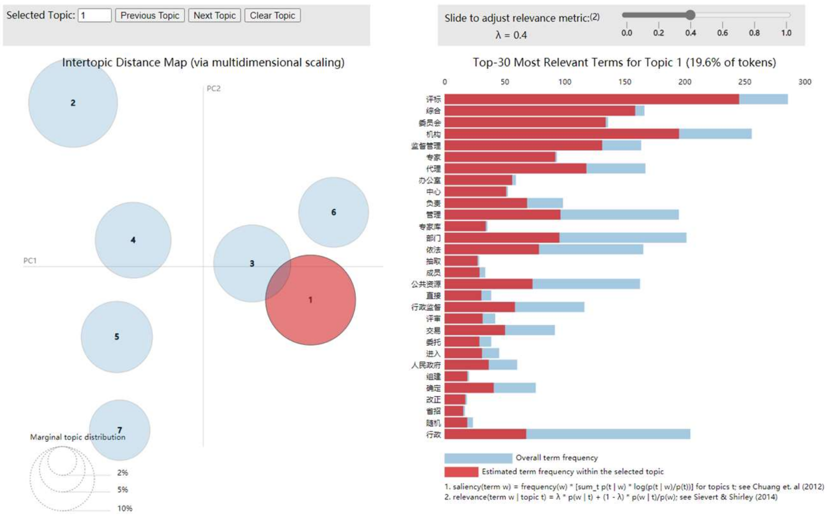


Figure 4. The inter-topic distance map and top-30 relevant terms for topic 4 in the region of high collusive bidding. Note: the Chinese in the image corresponds to Topic 1 in **Table 2**.

Table 1 corresponds to the final topic classification results derived from **Figure 3**, which includes seven topics. From **Table 1**, it infers that the main topic words for Topic 1 consist of verbs such as "improve," "develop," "strengthen," "formulate," "perfect," "optimize," and nouns like "system," "mechanism," and "supervision." Therefore, this topic is summarized as "improve the system and supervision." Topic 2's main topic words are related to electronic systems, platform, and participants, leading to its summary as "electronic information platform." Topic 3 includes topic words primarily associated with fines, penalties, and violations, thus summarized as "punishment measures." The main keywords for Topic 4 pertain to complaints, regulation, verification, and notification, leading to its summary as "external regulation." Topic 5's keywords are mainly related to the normativity and integrity requirements of the bidding process, resulting in its summary as "integrity requirements for bidding process." Topic 6's keywords describe the requirements concerning bidding materials, thus summarized as "bidding material requirements." Topic 7's keywords are primarily related to the bidding process, such as evaluation location and bidding methods, leading to its summary as "bidding process requirements." Based on the results from **Figure 3** and **Table 2**, the importance of topics in policy texts from regions with fewer collusive practices can be ranked as follows: "improve the system and supervision," "electronic information platform," "punishment measures," "external regulation," "integrity requirements for bidding process," "bidding material requirements," and "bidding process requirements."

Table 2 presents the final topic classification results derived from **Figure 4**, encompassing seven distinct topics. Topic 1's main topic words primarily encompass various institutions, stages, and participants in the bidding process, leading to its summary as "bidding process." Topic 2 contains frequent keywords related to bidding materials, resulting in its categorization as "bidding material requirements." Topic 3 has a significant presence of words related to integrity and regulation, such as "dishonesty," "blacklist," "law," and "management." Therefore, this topic is summarized as "integrity and regulation." Topic 4 includes a substantial number of keywords associated with bidding projects and bidding requirements, leading to its summary as "bidding requirements." Topic 5's keywords involve various government agencies, misconduct, evidence collection, and punishment-related terms, leading to its categorization as "violation handling." Topic 6's keywords are mainly related to the government and legal regulations, resulting in its summary as "government regulations." Topic 7's keywords encompass a wide range of content related to electronic and informational aspects. Therefore, Topic 7 is summarized as "electronic bidding platform." Based on the results from **Table 2**, the importance of topics in policy texts from regions with higher collusive practices can be ranked as follows: "bidding process," "bidding material requirements," "integrity and regulation," "bidding requirements," "violation handling," "government regulations," and "electronic bidding platform".

Table 1. The vocabulary distribution of different topics in the region of low collusive bidding.

Topic No.	Topic	Vocabulary
Topic1	Improve the system and supervision	Work, development, reform, supervision, department, mechanism, administrative supervision, regulation, strengthening, environment, field, formulation, system, improvement, notice, activity, market, optimization, development
Topic 2	Electronic information platform	procurement, expert, government, agency, platform, bid evaluation, electronic system, electronic, extraction, institution, system, Budget, expert pool, committee, irregularities, transaction system, commission, business
Topic 3	Punishment	Fine, discretion, amount, regulation, punishment, income, illegal, violation, division, disapproval, circumstances, confiscation, order, concomitant punishment, regulations, items, implementation, person in charge
Topic 4	External supervision	Complaint, processing, acceptance, decision, matter, investigation, proposal, making, rule, regulatory authority, related party, interest, reply, signature, order, superior, verification, notification, approval, objection
Topic 5	Integrity requirements	Management, publicity, candidates, credit, contract performance, information, results, bid winning, evaluation, construction, disclosure, contract, security deposit, announcement, proof, data, letter of guarantee, public resources, transaction, government affairs
Topic 6	Tender material requirements	Document, qualification, pre-examination, condition, method, spot check, law, catalog, modification, normative, plan, adoption, compilation, clarification, method, letter of commitment, review, regulation, announcement, requirement, filing
Topic 7	Bid evaluation related	Bid evaluation, bid opening, committee, evaluation, notification, name, violation, invitation, place, consortium, finance, notarization, members, contract, award, screening, address, name, organization, deadline

Table 2. The vocabulary distribution of different topics in the region of high collusive bidding.

Topic No.	Topic	Vocabulary
Topic1	Bidding process	Bid evaluation, committee, institution, supervision and management, expert, agent, office, center, responsible, management, department, law, members, public resources, administrative supervision, review, transaction, entrustment, government, expert pool
Topic 2	Tender material requirements	Qualification, examination, document, qualified, applicant, pre-examination, contract, announcement, conclusion, filing, deposit, post-examination, bid winning, submission, notice, bid winner, request, project, preparation, contract performance, agreement, submission for approval, selection, clear, agree, issue, evade
Topic 3	Integrity and Regulation	Project, engineering, regulation, activity, method, construction project, dishonesty, administration, blacklist, law, formulation, country, disclosure, public resource, management, approval, punishment
Topic 4	Bidder requirements	Registration, construction engineer, engineering, construction in progress, production, construction, license, interest, change, Damage, legal rights, post, construction project, division, maintenance, enterprise, remote, execution, key, professional, road, remote, Inquiry, security, validity period, experience
Topic 5	Punishment related	Housing, urban and rural construction, bad behavior, acquisition, records, supervision, identification, construction, cities, falsification, equivalent, punishment, commitment, reporting, defrauding, clues, civilization, construction bureau, construction office, proof
Topic 6	Government regulation	Funds, use, accountability, responsibility, violation, international, project, government, loan, state-owned enterprise, foreign, regulation, investment, law, scoring, appointment and dismissal, regulations, provincial organs, state, enterprise credit, supervision agency, aid, holding
Topic 7	Electronic bidding platform	Credit, evaluation, information, process, electronation, leakage, sharing, memorandum, serious demerit, disciplinary action, heavier, downgrade, dismissal, bad information, signature, transaction system, intelligent, public resource, warning, platform

5. Findings and discussion

The thematic analysis reveals that the region of low collusive bidding prioritizes continuous improvement and development of the bidding system and supervision. However, the highly collusive bidding area prioritizes the keywords of the bidding process. The policy texts related to electronic information platforms in regions with less collusion outdistance those in regions with high collusion. The results demonstrate that the widespread adoption of electronic and information technology in the bidding system positively impacts the governance of collusive bidding. This is because the integration of various modern collusive bidding monitoring technologies effectively reduces collusion occurrences. Nevertheless, the implementation of these regulatory technologies requires a unified electronic information platform. Thus, constructing an electronic information platform for bidding becomes crucial for effective digital collusion supervision. Ishii's [42] research found that the adoption of e-procurement may reduce bid rigging in public auctions by limiting in-person meetings of bidders. This study verified the above result in different ways. However, it is important to consider the cost of building digital supervision systems. The government should encourage R&D agencies to explore cost-effective techniques for digital supervision.

The study also finds that policy texts in regions with low collusion reference the investigation and punishment more. The finding means that the investigation and punishment have a specific deterrent effect on collusive bidding. Zhu et al. [9] propose a system dynamics model to present the deterrence of punitive measures. The results also verified that punitive measures could mitigate bidders' collusion behavior in the construction industry. Besides, Wang et al. [26] and Oke et al. [27] show that the main reason for collusive biding lies in the lack of punishment. Thus, some scholars suggest that the occurrence of collusive bidding can be reduced by increasing the punishment [27,30]. Wang et al.'s [41] research shows that the fine of the Chinese government to collusive bidders is much lower than the rational deterrence value. Therefore, the Chinese government should enhance penalties to mitigate bidders' collusion behavior. However, different countries may be facing different reasonable deterrent scopes due to various influencing factors, such as the economic level and social environment. Thus, the researchers should be doing more work to explore the reasonable deterrent scope by the character of their country's construction industry, thereby reducing bidders' collusive behaviors. Furthermore, these studies have overlooked the significance of thorough investigation. The research highlights the importance of directing attention towards probing instances of collusive bidding.

The study also shows that areas with lower collusive bidding focus more on external supervision, which means that strengthening external supervision positively affects the governance of collusive bidding. Regarding the external supervision, whistleblowing is one of the mechanisms for the internal control system to reduce the fraud [43]. From the extraction results of the subject words of the policy texts in areas with lower collusive bidding, it can be concluded that the whistleblowing occupies a very high proportion. In contrast, the ratio of policy texts in regions with frequent collusive bidding cases is meager. The above results show that whistleblowing is effective in the governance of collusive bidding. Therefore, this study believes that the government should set up various convenient ways to actively encourage all parties involved, social figures, and the news media to report on collusion in project bidding and encourage whistleblowers to provide evidence that can evaluate the collusion between the reported persons. For example, filming the secret communication between colluding bidders, formulating bidding documents, distributing benefits, etc. In addition, the government should do an excellent job of protecting whistleblowers to ensure that whistleblowers perceive that their reporting behavior will not bring them adverse effects, such as when an online reporting platform is set up and whistleblowers can report anonymously. In addition, the exposure and credit mechanism can have a specific negative impact on colluding enterprises and form a particular warning effect on other enterprises. The credit record and exposure mechanism will affect the evaluation of the enterprise by the owner in the later bidding process. Consequently, this study suggests that the government can initiate an external supervision mechanism by implementing monitoring, reporting, and exposure systems. This mechanism would be led by the government and involve joint supervision by all relevant parties, including the public and the media.

6. Conclusions

Collusive bidding poses a significant threat to the health and sustainable development of the construction industry. The enactment of proficient policy measures is a potent means to alleviate collusive bidding within the construction sector actively. As such, this research analyses bidding policies between regions characterized by low and high instances of collusive bidding. By identifying disparities in policy contents, the study aims to identify efficacious governance strategies that are more effective to fight for collusive bidding in the construction industry. The research found that adopting an electronic bidding platform, imposing penalties for joining the investigation, and reinforcing external supervision are constructive forces in mitigating collusive bidding.

The research findings give policy insights into the most critical governance strategies for addressing collusive bidding from a policy-oriented perspective. The research findings also provide valuable guidance for researchers to further develop the more efficacious electronic bidding system integration of various modern collusive bidding monitoring technologies and suggestions in the development of external supervision.

It is important to acknowledge one limitation in this research. The policies collected in this study are from China, a vast nation comprising numerous provinces, each with its own distinct bidding regulations. These inherent attributes have significantly facilitated the completion of our research. However, some small countries may find it challenging to repeat this research in their countries due to the unavailability of data. Nonetheless, these nations can leverage the results derived from this study to formulate more effective methods for mitigating collusive bidding practices in their respective contexts.

Author contributions: Conceptualization, XW; methodology, XW and YZ; software, XW and YZ; validation, XW, YZ and KC; formal analysis, KC; investigation, YZ;

resources, XW; data curation, YZ; writing—original draft preparation, XW; writing—review and editing, KC and YZ; visualization, XW; supervision, XW. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Wang X, Owusu EK, Ye K. Impacts of External Environmental Factors on the Collusive Team Scale in Bidding: The Case of China. Journal of Management in Engineering. 2023; 39(4). doi: 10.1061/jmenea.meeng-5270
2. Chotibhongs R, Arditi D. Analysis of collusive bidding behavior. Construction Management and Economics. 2012; 30(3): 221-231. doi: 10.1080/01446193.2012.661443
3. Shan M, Chan APC, Le Y, et al. Understanding Collusive Practices in Chinese Construction Projects. Journal of Professional Issues in Engineering Education and Practice. 2017; 143(3). doi. 10.1061/(asce)ei.1943-5541.0000314
4. Souhu. Suspects of bidding rigging in Fengcheng power plant accident that caused more than 70 deaths were repatriated (Chinese). Available online: https://www.sohu.com/a/143592434_805762 (accessed on 15 September 2024).
5. Souhu. The pass rate of the pile foundation is 0! The construction unit compensated 108 million yuan! The 800 million "problem road" bidders were sentenced! Many people have been arrested before. Available online: https://www.sohu.com/a/473060028_121123774 (accessed on 15 September 2024).
6. Wang X, Ye K, Arditi D. Embodied cost of collusive bidding: evidence from China's construction industry. Journal of Construction Engineering and Management. 2021; 147(6): 04021037. doi. 10.1061/(ASCE)CO.1943-7862.0002044
7. Shi HB, Li XW, Xu HJ. Game Analysis on Collusion Tender in the Construction Projects Bidding. Applied Mechanics and Materials. 2013; 357-360: 2414-2419. doi: 10.4028/www.scientific.net/amm.357-360.2414
8. Shan M, Le Y, Yiu KTW, et al. Assessing Collusion Risks in Managing Construction Projects Using Artificial Neural Network. Technological and Economic Development of Economy. 2018; 24(5): 2003-2025. doi: 10.3846/20294913.2017.1303648
9. Zhu W, Zheng Y, Ye K, et al. Deterrence of Punitive Measures on Collusive Bidding in the Construction Sector. Complexity. 2021; 2021: 1-12. doi: 10.1155/2021/9913413
10. Wang X, Arditi D, Ye K. Coupling Effects of Economic, Industrial, and Geographical Factors on Collusive Bidding Decisions. Journal of Construction Engineering and Management. 2022; 148(7). doi: 10.1061/(asce)co.1943-7862.0002291
11. Long W, Wang X, Liang Y, et al. Characteristics of Collusive Practices in Bidding: Mixed Methods Study in China. Journal of Construction Engineering and Management. 2023; 149(6). doi: 10.1061/jcemd4.coeng-12938
12. Wang X, Long W, Sang M, et al. Towards Sustainable Urbanization: Exploring the Influence Paths of the Urban Environment on Bidders' Collusive Willingness. Land. 2022; 11(2): 280. doi: 10.3390/land11020280
13. Brown J, Loosemore M. Behavioral factors influencing corrupt action in the Australian construction industry. Engineering, Construction and Architectural Management. 2015; 22(4): 372-389. doi: 10.1108/ecam-03-2015-0034
14. Roux C, Thöni C. Collusion among many firms: The disciplinary power of targeted punishment. Journal of Economic Behavior & Organization. 2015; 116: 83-93. doi: 10.1016/j.jebo.2015.03.018
15. Tabish SZS, Jha KN. The impact of anti-corruption strategies on corruption free performance in public construction projects. Construction Management and Economics. 2012; 30(1): 21-35. doi: 10.1080/01446193.2011.654128
16. Harrington JE. Penalties and the deterrence of unlawful collusion. Economics Letters. 2014; 124(1): 33-36. doi: 10.1016/j.econlet.2014.04.010
17. Cheng Z, Ke Y, Yang Z, et al. Diversification or convergence. Engineering, Construction and Architectural Management. 2020; 27(6): 1315-1335. doi: 10.1108/ecam-06-2019-0290
18. Morselli C, Ouellet M. Network similarity and collusion. Social Networks. 2018; 55: 21-30. doi: 10.1016/j.socnet.2018.04.002
19. Zhang B, Le Y, Xia B, Skitmore M. Causes of Business-to-Government Corruption in the Tendering Process in China. Journal of Management in Engineering. 2017; 33(2): 05016022. doi. 10.1061/(asce)me.1943-5479.0000479
20. Baranes E, Mirabel F, Poudou JC. Collusion Sustainability with Multimarket Contacts: Revisiting HHI Tests. Theoretical Economics Letters. 2012; 2(3): 307-315. doi: 10.4236/tel.2012.23057
21. Bolotova Y, Connor JM, Miller DJ. The impact of collusion on price behavior: Empirical results from two recent cases.

International Journal of Industrial Organization. 2008; 26(6): 1290-1307. doi: 10.1016/j.ijindorg.2007.12.008
22. Dorée AG. Collusion in the Dutch construction industry: An industrial organization perspective. Building Research & Information. 2004; 32(2): 146-156. doi: 10.1080/0961321032000172382
23. Price MK. Using the Spatial Distribution of Bidders to Detect Collusion in the Marketplace: Evidence from Timber Auctions. Journal of Regional Science. 2008; 48(2): 399-417. doi: 10.1111/j.1467-9787.2008.00557.x
24. Ratshisusu H. Limiting collusion in the construction industry: A review of the bid-rigging settlement in South Africa. Journal of Economic and Financial Sciences. 2014; 7(4): 587-606. doi: 10.4102/jef.v7i4.386
25. Stigler GJ. A Theory of Oligopoly. Journal of Political Economy. 1964; 72(1): 44-61. doi: 10.1086/258853
26. Wang X, Liu R, Ye K, Tekka RS. Modelling the cost of collusion in the construction industry: a case of China. In: Proceedings of the 36th Annual ARCOM Conference; UK: Association of Researchers in Construction Management; 7-8 September 2020; UK.
27. Oke A, Aigbavboa C, Mangena Z. Prevention of Collusion for Innovative Construction. Procedia Engineering. 2017; 196: 491-497. doi: 10.1016/j.proeng.2017.07.229
28. Tirole J. Collusion and the theory of organizations. Advances in Economic Theory: Sixth World Congress. 1992; 2(1): 1-25.
29. Allain ML, Boyer M, Kotchoni R, et al. Are cartel fines optimal? Theory and evidence from the European Union. International Review of Law and Economics. 2015; 42: 38-47. doi: 10.1016/j.irle.2014.12.004
30. Katsoulacos Y, Motchenkova E, Ulph D. Penalizing cartels: The case for basing penalties on price overcharge. International Journal of Industrial Organization. 2015; 42: 70-80. doi: 10.1016/j.ijindorg.2015.07.007
31. Morgan EJ. Controlling cartels—Implications of the EU policy reforms. European Management Journal. 2009; 27(1): 1-12. doi: 10.1016/j.emj.2008.04.006
32. Zarkada-Fraser A. A Classification of Factors Influencing Participating in Collusive Tendering Agreements. Journal of Business Ethics. 2000; 23(3): 269-282. doi. 10.1023/A:1006210308373
33. Chotibhongs R, Arditi D. Detection of Collusive Behavior. Journal of Construction Engineering and Management. 2012; 138(11): 1251-1258. doi. 10.1061/(asce)co.1943-7862.0000542
34. Ballesteros-Pérez P, González-Cruz MC, Cañavate-Grimal A, et al. Detecting abnormal and collusive bids in capped tendering. Automation in Construction. 2013; 31: 215-229. doi: 10.1016/j.autcon.2012.11.036
35. Erfani AK, Zhang, Cui Q. TAB Bid Irregularity: Data-Driven Model and Its Application. Journal of Management in Engineering. 2021; 37(5): 04021055. doi: 10.1061/(ASCE)ME.1943-5479.0000958
36. Porter RH, Zona JD. Detection of Bid Rigging in Procurement Auctions. Journal of Political Economy. 1993; 101(3): 518-538. doi: 10.2307/2138774
37. Padhi SS, Mohapatra PKJ. Detection of collusion in government procurement auctions. Journal of Purchasing and Supply Management. 2011; 17(4): 207-221. doi: 10.1016/j.pursup.2011.03.001
38. Padhi SS, Wagner SM, Mohapatra PKJ. Design of Auction Parameters to Reduce the Effect of Collusion. Decision Sciences. 2015; 47(6): 1016-1047. doi: 10.1111/deci.12159
39. Pulid. Peking University Legal Information Database. 2021. Available online: https://www.pkulaw.com/ (accessed on 15 September 2024).
40. Danesh F, Dastani M, Ghorbani M. Retrospective and prospective approaches of coronavirus publications in the last half-century: A Latent Dirichlet allocation analysis. Library Hi Tech. 2021; 39(3): 855-872. doi: 10.1108/lht-09-2020-0216
41. Wang X, Ye K, Chen M, Yao Z. A Conceptual Framework for the Inclusion of Exogenous Factors into Collusive Bidding Price Decisions. Journal of Management in Engineering. 2021; 37(6): 04021071. doi. 10.1061/(asce)me.1943-5479.0000981
42. Ishii R. Can E-Procurement Reduce Bid Rigging in Public Auctions? Journal of Competition Law & Economics. 2021; 18(2): 456-482. doi: 10.1093/joclec/nhab019
43. Mohamed N, Marsam AD, Abu NA, et al. Civil servants' responses on whistleblowing towards better governance. Revista de Ciencias Sociales y Humanidades. 2019; 4(16): 132-135.

Building Engineering 2024, 2(2), 1811.
https://doi.org/10.59400/be.v2i2.1811

Article

Evaluating the damage of collapsed bridges using remote sensing technologies: Case study: Baltimore's Francis Scott Key Bridge

Reedhi Shukla*, Sampath Kumar Pabbisetty, Satish Jayanthi, Kamini Janardhanan

National Remote Sensing Centre, ISRO, Hyderabad 500037, India
*** Corresponding author:** Reedhi Shukla, Reedhi_shukla@nrsc.gov.in

CITATION

Shukla R, Pabbisetty SK, Jayanthi S, Janardhanan K. Evaluating the damage of collapsed bridges using remote sensing technologies: Case study: Baltimore's Francis Scott Key Bridge. Building Engineering. 2024; 2(2): 1811. https://doi.org/10.59400/be.v2i2.1811

ARTICLE INFO

Received: 15 June 2024
Accepted: 7 August 2024
Available online: 21 August 2024

Abstract: Bridges are vital for linking communities and facilitating economic activity. However, in the face of disaster, like ship collisions pose a significant threat to bridge infrastructure, causing structural damage and potential safety hazards. Rapid and precise assessment of the damage is essential for effective emergency response and recovery operations. Remote sensing with near-real-time satellite imagery provides the disaster scenario. This paper presents a change detection using pre- and post-disaster satellite data for Baltimore's Francis Scott Key Bridge to identify structural damage due to the collision of the ship with support pillars on 26 March 2024. Both optical and microwave satellite data were used from open data sources and analyzed based on geospatial techniques such as change detection and surface profiling. It is estimated that an 1100-meter span of bridge was affected due to this collision, which helped to estimate the damage and mobilize the rescue operations. It may need further validation from ground truth information. Hence, the current study emphasizes the potential of remote sensing satellite data to provide near-real-time impact on disaster analysis.

Keywords: Scott Key Bridge; ship collisions; multi-spectral; optical; SAR; geospatial analysis

1. Introduction

Bridges are vital components of transportation networks, facilitating the movement of goods and people. However, sudden bridge failures lead to loss of human life and economic losses. Traditional damage assessment methods are often time-consuming and pose risks to the surveyors. Near-real-time data of post-disaster scenarios and alerting systems can expedite the emergency response to save more lives. Satellite data has emerged as a valuable tool in assessing the damage to collapsed bridges, providing high-resolution imagery that offers a comprehensive overview of the disaster site.

Researchers have increasingly explored using satellite data for post-disaster assessments, leveraging its ability to capture detailed information on the extent and severity of structural damage. This literature review examines key studies and methodologies in utilizing satellite data for evaluating the damage of collapsed bridges, focusing on the case study of Baltimore's Francis Scott Key Bridge. It is demonstrated the effectiveness of satellite imagery in disaster assessment, using deep learning techniques to analyze flood damage [1]. Their study highlights the potential of satellite data for detecting and mapping structural damage to infrastructure, including bridges, following natural disasters. Research by Jaboyedoff et al. [2] showcases the effectiveness of LiDAR in landslide investigations and suggests its applicability in bridge damage assessment. LiDAR scans provide detailed three-dimensional models of the disaster site, allowing for the identification of subtle deformations and cracks in bridge components. Gonzalez-Jorge et al. [3] discuss using UAVs and artificial intelligence to revolutionize bridge inspection and maintenance practices. Adams and Friedland have explained how pre- and post-disaster image comparisons and object change detection algorithms enable researchers to visualize and quantify bridge damage accurately [4]. Jaboyedoff et al. have studied the Gorkha earthquake in Nepal and demonstrated the effectiveness of this approach in post-disaster damage assessment [2]. Besides optical imagery, SAR can acquire imagery independent of weather conditions or daylight, which plays a vital role in post-disaster assessment. Ehrlich et al. explain how integrating machine learning models with SAR data enhances the accuracy and efficiency of damage assessment [5]. Despite the advancements in satellite data, getting real-time data on disasters with alert-based systems is still challenging. The case study of Baltimore's Francis Scott Key Bridge study can aid in understanding the potential of both optical and microwave remote sensing data for near real-time analysis and assessment of the scenario.

2. Materials and methods

2.1. Study area and data sets

The Baltimore's Francis Scott Key Bridge, located (**Figure 1**) at 39°13′1″ N 76°31′42″ W, inaugurated 47 years ago on 23 March 1977, is a steel arch continuous through a truss bridge that extends across the lower Patapsco River. Comprising two primary spans, supported by an array of concrete piers and steel trusses, the bridge stretches over approximately 1.6 miles (2.6 km). It was operated by the Maryland Transportation Authority (MDTA) and carried an estimated 11.5 million vehicles annually. The bridge and four-lane approaches carried vehicles of all sizes, including many trucks carrying hazardous materials. They formed the outermost of three toll crossings of Baltimore's harbor, including the Baltimore Harbor and Fort McHenry tunnels. On 26 March 2024, at 01:28 EDT (05:28 UTC), the main spans of the bridge collapsed after the Singapore-registered container ship MV Dali lost power [6] and collided with the southwest supporting pier of the main truss section. The evaluation commences by obtaining high-resolution satellite data of the Francis Scott Key Bridge as explained in the flowchart (**Figure 2**). In order to access the damage after the collision and bridge damage, multiple cloud-free datasets were explored using Sentinel-hub for the date range between 18 March and 26 March.

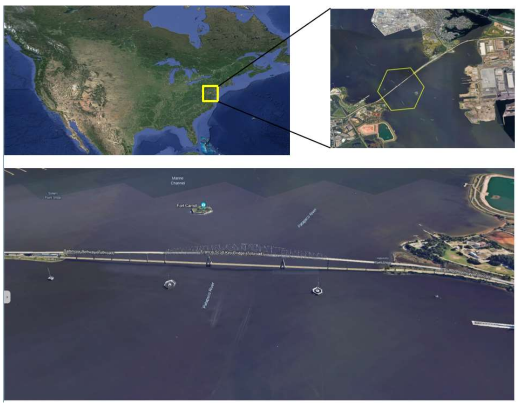


Figure 1. Study area ref (google earth).

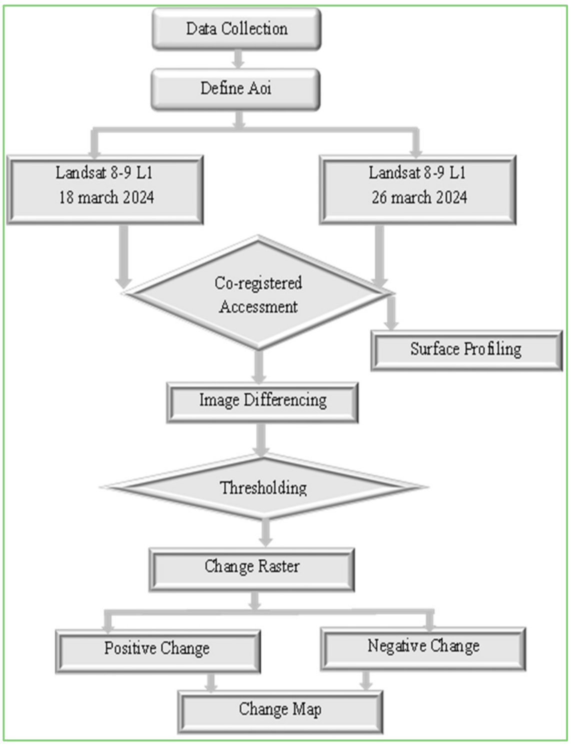


Figure 2. Methodology.

For the pre-disaster, before 26 March, multiple cloud-free data sets were available, but post-disaster, only one cloud-free scene, Landsat 8–9 L1, was available in the open source domain. For this study, pre-disaster T1 Landsat 8–9 L1 dated 18 March 2024 (**Figure 3**) and post-disaster T2 Landsat image 8–9 L1 dated 26 March 2024 (**Figure 4**) are taken into consideration. To further study the area, optical images of the post-disaster scenario were sought; however, due to cloud coverage, the disaster site needed to be visible. VVVH radiometric terrain-corrected Sentinel-1 SAR products from 17 March (**Figure 5**) and 29 March (**Figure 6**) were obtained to address this issue. SAR data offers unique capabilities such as all-weather, day-and-night operation, surface penetration, and high temporal resolution, which are crucial for change monitoring. The high temporal resolution provided by SAR satellites, like the Sentinel-1 mission, enables frequent monitoring of areas of interest, facilitating quantitative assessments of change detection by providing detailed information on surface characteristics. The Landsat 8 and 9 missions, a part of the Landsat program, have significantly enhanced our capabilities to observe and study Earth's surface changes through their L1 level data. The Landsat 8 and 9 satellites have a combined revisit time that significantly improves the temporal resolution of observations made of Earth's surface, offering revisits every eight days at the equator under optimal conditions. Roy et al. [7] and Wulder et al. [8] have explained that improved temporal granularity facilitates more frequent monitoring of changes, which is crucial for applications like post-disaster analysis. Roy et al. have studied that despite better receptivity and swath offered by Landsat 8–9 multi-spectral satellites (bands 2, 3, and 4), challenges such as cloud cover pose limitations to getting post-disaster scenarios [7]. The Sentinel-1 and Sentinel-2 missions are key components of the Copernicus Programme, which is an initiative by the European Union to provide ongoing, thorough, and self-sufficient Earth observation capabilities. First, the Sentinel-2 was explored for the study, but due to cloud cover, the data was not available. Sentinel-1 is outfitted with C-band Synthetic Aperture Radar (SAR) instruments, allowing them to gather imagery regardless of the time of day or weather conditions. A notable advantage of the Sentinel-1 mission is its open data policy, overseen by the European Space Agency (ESA). This policy ensures that Sentinel-1 data is freely accessible to users worldwide, promoting extensive use for scientific research and practical applications. Marino et al. have explained how the availability of Sentinel-1 data (VV and VH polarizations) has spurred innovation in Earth observation, making substantial contributions to areas such as post-disaster analysis [9].

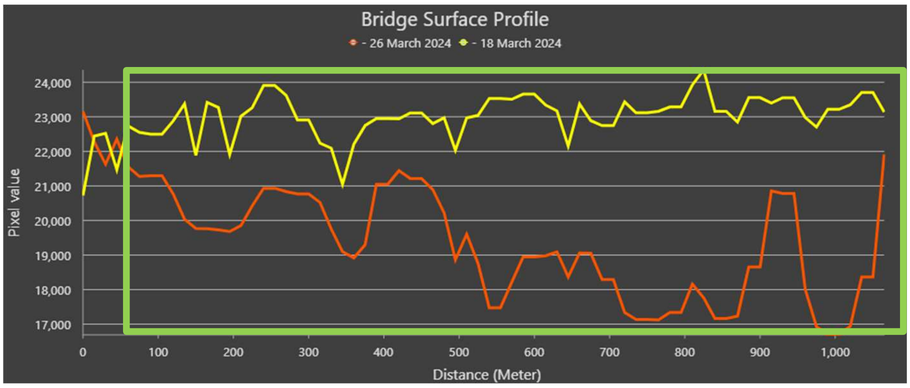


Figure 3. Surface profiling of the pre (18 march 2024) and post (26 march 2024) images.

Figure 4. 18 March 2024—Pre collision.

Figure 5. 26 March 2024—Post collision.

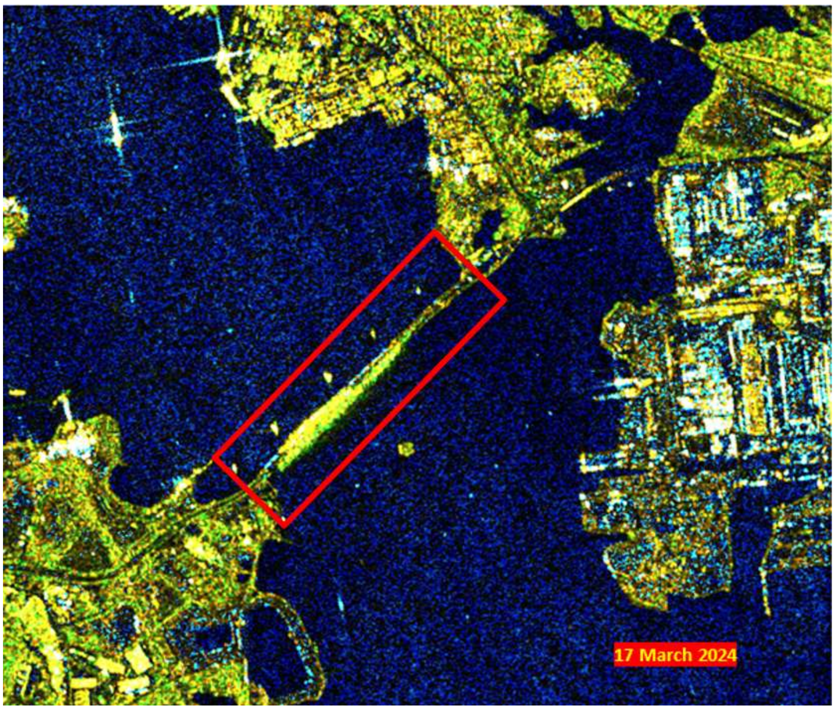


Figure 6. 17 March 2024—Pre collision.

2.2. Methodology

The evaluation commences by obtaining high-resolution satellite data of the Francis Scott Key Bridge in Baltimore on 26 March 2024 (**Figure 2**). To determine the damage's extent and location, pre-disaster images were selected meticulously, considering factors such as clarity, absence of cloud cover, and relevance to the disaster's timeline. Post-disaster images were chosen to closely monitor the event and capture immediate impacts. GIS software was employed to conduct image differencing, classifying changes, and surface profiling based on their intensity and type, as seen in **Figure 4**.

2.2.1. Raster surface profiling

Surface profiling (**Figure 3**) offers a compelling approach to examining surface changes in multi-temporal Landsat image bands 4, 3, and 2 with true color composite. Each pixel within Landsat holds valuable information about reflectance. Extracting surface profiles along the same transect over a bridge can derive T1 and T2 sets of reflectance values. The comparison of these profiles allows for the detection of significant discrepancies, as shown in Chart 1, which may indicate changes in the ground, such as bridge damage. Visualizing these profiles on a graph facilitates the comparison process, unveiling patterns like damage, cracks or gaps, and alterations in the surface. Inherent reflectance information is calculated within each Landsat pixel to extract surface profiles along a defined transect over a bridge at two distinct time points (T1 and T2) to extract surface profiles along a designated transect across the bridge in both T1 and T2 imagery. The extracted T1 and T2 reflectance profiles are then compared to identify potential changes in the bridge structure. Combining surface profiling with other change detection techniques and pertinent data sources can give a clear picture of the changes that happened over time.

2.2.2. Image differencing

Combining surface profiling with the image differencing method provides valuable insights into potential bridges. In this study, the difference in two raster images involves quantifying the changes in pixel values. L1 corresponds to the pre-disaster imagery T1 Landsat 8–9 L1 dated 18 March (**Figure 4**), and T2 Landsat image 8–9 L1 dated 26 March 2024 (**Figure 5**). Pixel values of the first raster image are denoted as T1(x,y) and the second raster image as T2(x,y), where x and y represent the spatial coordinates of the pixels. The change in two raster is calculated by subtracting the pixel values of the T1 from the corresponding pixel values of the T2 raster image. The resulting change value indicates how much each pixel has changed between the two images. Positive values indicate an increase in the surface that is clearly visible as the ship is present at the collision point, while negative values clearly depict the damage to the bridge.

$$\text{Change}(x,y) = \text{T1}(x,y) - \text{T2}(x,y)$$

The change raster (**Figure 7**) shows the damaged bridge's portion as bright pixels showcase the damaged portion of the bridge.

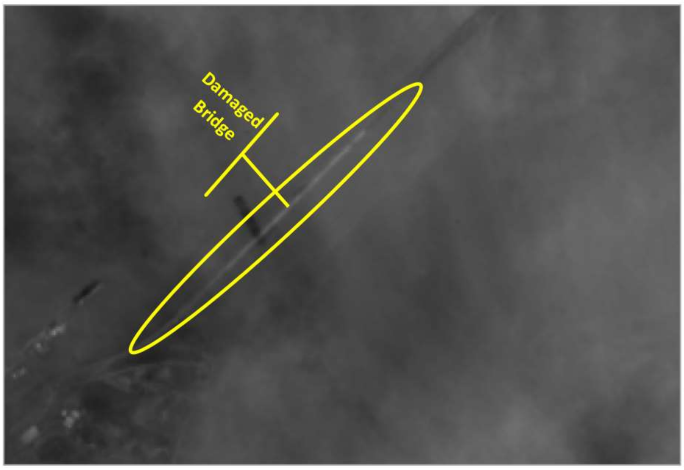


Figure 7. Difference raster ship collision coordinates: 76.5294487° W, 39.2159581° N. Extent of damage to the Bridge: 1100 m (approx.).

2.2.3. SAR data interpretation

To further study the area, optical images of the post-disaster scenario were explored; however, due to cloud coverage, the disaster site was not clearly visible. To address this, a comprehensive investigation of the impact of the bridge collapse was conducted using VVVH radiometric terrain-corrected Sentinel-1 SAR data obtained on 17 March (pre-disaster) (**Figure 6**) and 29 March (post-disaster) (**Figure 8**). VVVH records backscatter in the polarizations of horizontal transmits and horizontal receive (HH) and vertical transmit and vertical receive (VV). Thus, by comparing the VV and HH returns, even little variations in the bridge structure can be found. The high temporal resolution and better spatial resolution provided by SAR satellites, like the Sentinel-1 mission, enable frequent monitoring of areas of interest, facilitating quantitative assessments of change detection by providing finer details of structures. The integration of multi-polarization, high spatial resolution, and RTC enabled the measurable enhancement in calculating the damage assessment. The entire picture of the bridge's state provided by this SAR-derived data clearly highlights the changes and damage to the bridge resulting from the collision. The visual interpretation of SAR data complements the optical analysis, confirming the damage to the bridge with better efficacy and precision.

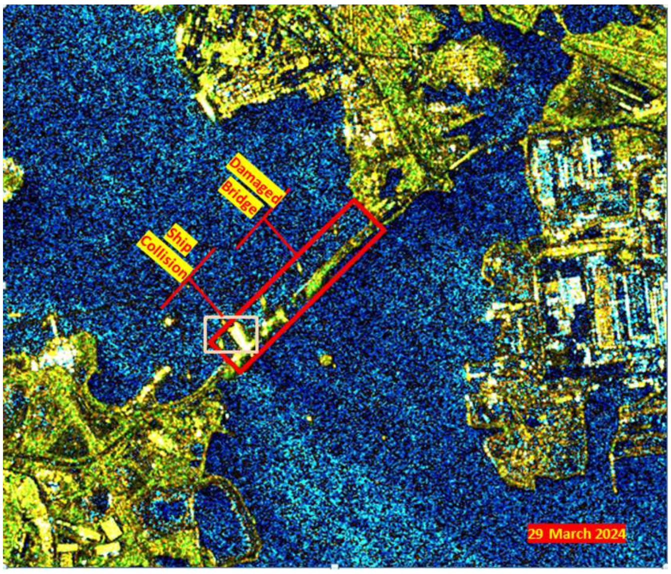


Figure 8. 29 March 2024—Post collision.

3. Results and conclusion

The collision incident in Baltimore has caused considerable damage to the Francis Scott Key Bridge, as indicated by our analysis. By using Landsat 9 L1 True color-pan-sharpened imagery, we were able to identify clear differences between the conditions before and after the collision. In the post-disaster imagery, the absence of the bridge structure was particularly notable. Further analysis through surface profiling and pixel value comparisons allowed us to estimate the extent of the damage to be around 1100 m. The evaluation commenced with the acquisition of Landsat imagery, with the post-disaster image dated 26 March 2024, revealing substantial damage to the bridge structure. Surface profiling using Band 1 highlighted notable differences in pixel values between pre- and post-disaster images, indicating the absence of the bridge in the latter. Optical images from both dates were utilized to calculate the extent of damage, estimated to be approximately 1100 m. This result shall aid various teams involved in decision-making, rescue, and relief operations to quickly assess the damage and mobilize the resources from remote locations, as in making policies for any such event in the future.

To mitigate cloud coverage issues hindering post-disaster optical imagery analysis, VVVH radiometric terrain-corrected Sentinel-1 SAR products from 17 March and 29 March were obtained. SAR data, with its unique capabilities, including all-weather operation and high temporal resolution, confirmed the observed damages and provided valuable insights into surface characteristics. The fusion of SAR and optical data facilitated a comprehensive assessment of damages, highlighting the complementary nature of these datasets in disaster management applications.

Further research is necessary to advance the capabilities of remote sensing technologies in disaster management. Advanced data fusion algorithms and automated damage detection methodologies can improve the efficiency and accuracy of damage assessments. Additionally, the development of alert-based systems for real-time monitoring of disaster events can facilitate proactive response measures, minimizing loss of life and property.

Author contributions: Conceptualization, RS; methodology, RS and SKP; software, RS and SKP; validation, RS, SKP, SJ and KJ; formal analysis, RS and SJ; writing—RS; writing—review and editing, RS and SKP. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Yang L, Cervone G. Analysis of remote sensing imagery for disaster assessment using deep learning: a case study of flooding event. Soft Computing. 2019. doi: 10.1007/s00500-019-03878
2. Jaboyedoff M, Oppikofer T, Abellán A, et al. Use of LIDAR in landslide investigations: a review. Natural Hazards. 2010; 61(1): 5-28. doi: 10.1007/s11069-010-9634-2
3. Gonzalez L, Montes G, Puig E, et al. Unmanned Aerial Vehicles (UAVs) and Artificial Intelligence Revolutionizing Wildlife Monitoring and Conservation. Sensors. 2016; 16(1): 97. doi: 10.3390/s16010097
4. Adams BJ, Friedland CJ. Rapid response systems for disaster management. Disaster Prevention and Management. 2015; 24(1): 86-99.
5. Ehrlich D, Guo H, Molch K. Remote sensing support for post disaster recovery management. International Journal of Remote Sensing. 2009; 30(13): 3383-3396.
6. The New York Times. Baltimore Bridge Collapse. Available online: https://www.nytimes.com/live/2024/03/26/us/baltimore-bridge-collapse/370a20f1-0d44-5d22-ab69-e3b5f1c8bde4?smid=url-share (accessed on 10 August 2024).
7. Roy DP, Wulder MA, Loveland TR, et al. Landsat-8: Science and product vision for terrestrial global change research. Remote Sensing of Environment. 2014; 145: 154-172. doi: 10.1016/j.rse.2014.02.001
8. Wulder MA, Coops NC, Roy DP, et al. Land cover 2.0. International Journal of Remote Sensing. 2018; 39(12): 4254-4284. doi: 10.1080/01431161.2018.1452075
9. Marino A, Ouchi K, Ferro-Famil L, et al. Advances in SAR: Sensors, Methodologies, and Applications. IEEE Transactions on Geoscience and Remote Sensing. 2018; 56(3): 1215-1231.

Building Engineering 2024, 2(2), 1440.
https://doi.org/10.59400/be.v2i2.1440

Article

Study on prediction model of nitrogen emission in the production stage of residential building materials—A case study of Guangdong province

Yue Lyu

School of Civil Engineering, Shaoxing University, Shaoxing 312000, Zhejiang Province, China; 53048830@qq.com

CITATION

Lyu Y. Study on prediction model of nitrogen emission in the production stage of residential building materials—A case study of Guangdong province. Building Engineering. 2024; 2(2): 1440. https://doi.org/10.59400/be.v2i2.1440

ARTICLE INFO

Received: 11 June 2024
Accepted: 31 July 2024
Available online: 12 August 2024

Abstract: This study aims to reduce nitrogen emissions from residential buildings and establishes a prediction model for nitrogen emissions during the production of building materials. The calculation boundary, content, and method of nitrogen emission in the production stage of residential building materials are accurately analyzed. Based on the nitrogen emission data of 20 residential buildings in Guangdong, the composition and distribution characteristics of nitrogen emission in the production stage of building materials are analyzed. The coupling relationship between building design parameters and building materials' nitrogen emissions is established using linear regression and ridge regression. 10 kinds of nitrogen emission prediction models based on the design parameters of residential buildings in the production stage of building materials were established and verified. The results show that the linear model M3, based on the number of floors above and below ground, the area width and depth, and the ridge regression model M5, based on the number of floors above and below ground, the area width and depth, and the total number of main functional rooms, have good fitting and prediction performance, respectively. The linear regression model M6, based on the number of floors above and below ground, the area width and depth, and the total number of rooms, has the best fitting and prediction performance. M3, M5, and M6 can accurately predict the nitrogen emission composition and distribution characteristics of building materials in residential building design and lay a foundation for future research on nitrogen emission evaluation and calculation methods and nitrogen emission reduction technology strategies.

Keywords: nitrogen emission; residential building; building material; production stage

1. Introduction

The carbon and nitrogen emissions of residential buildings in the operation and building materials production stages account for a large proportion of the entire life cycle of the building. According to the construction requirements and standards of green buildings, building materials and the indicators of building heat consumption have been controlled to a certain extent. More mature carbon emission evaluation, calculation methods, and emission reduction technologies have been developed for residential building materials in the production and operation stages. Still, for living building materials, there is little research on the relationship between nitrogen emission evaluation methods and design parameters of residential buildings in the production and operation stages.

At present, at the urban level, Malik [1] and others have established a multi-regional input-output database and evaluated the driving factors of nitrogen emissions by analyzing six determinants: nitrogen efficiency (nitrogen emissions per unit output), production formula (interdepartmental dependence), final demand composition (household consumption basket), final demand destination (consumption and investment balance), wealth (final consumption per capital), and population. Wu et al. [2] built a driving force analysis model based on the STIRPAT framework. Using spatial measurement methods, they quantitatively estimated the driving effect of population and land urbanization on ammonia nitrogen emissions. Wu et al. [3] proposed a fuel reprocessing method based on coal preheating to reduce NOx emissions. Liu et al. [4] used the WRF-EMEP model to quantitatively analyze the nitrogen emissions of three typical urban agglomerations in the Beijing Tianjin Hebei region, the Yangtze River Delta, and the Pearl River Delta through the standard deviation ellipse (SDE) "center of mass" migration method. McCourt and MacDonald [5] pointed out that the nitrogen footprint quantifies consumer-driven active nitrogen emissions. They provided an illustrative case study to estimate the drivers of local nitrogen emissions in Canada from the national nitrogen budget, nitrogen emission inventory, and statistical data. Jiang et al. [6] analyzed the socioeconomic drivers that can reduce NOx emissions based on satellite observation technology and spatial econometric models. Pan et al. [7], based on satellite data and long-term ground observation, proposed that reducing ammonia emissions is increasingly important for improving China's air quality. Xian et al. [8], based on the theory and connotation of pollution nitrogen footprint and greywater footprint, analyzed the main factors that increase the urban greywater footprint and studied the methods to give priority to quickly improve the reuse rate of urban domestic sewage and comprehensively improve the nitrogen removal rate of urban sewage.

At the architectural level, Cai et al. [9] studied the distribution behavior of nitrogen atoms in stainless steel by atomic probe tomography. Shan and Ren [10] determined oxygen and nitrogen in steel based on the inert gas melting infrared absorption method and the inert gas melting thermal conductivity method to ensure the accuracy of oxygen and nitrogen content analysis in steel. Shen et al. [11] designed an automatic detection method for the concentration of lower nitrogen oxide pollutants by applying photocatalyst materials in buildings. Li et al. [12] detected the mass concentration of nitrite ions in concrete by three methods, namely spectrophotometer, color difference determination, and direct arbitration. Their research has laid a foundation for the later research on nitrogen reduction of building materials; Tang [13], Zhao [14], Ma, and others [15] studied the method of reducing nitrogen oxide emissions of cement enterprises through staged combustion denitrogenation technology and SNCR denitrogenation technology. Zhu [16] reduced nitrogen oxide emissions of iron and steel enterprises by developing the method of short-process steelmaking. Yao et al. [17] pointed out that controlling nitrogen oxides is the key to reducing nitrogen oxides in steel, providing technical support for further reduction of nitrogen oxides in steel.

In the civil engineering industry, China has not yet formulated a standard prediction system for building nitrogen emissions; the primary data method is still the inventory statistics method. Therefore, based on the bill of quantities and construction drawings of the actual project, this study establishes a method to obtain the nitrogen emissions (dependent variables) of building materials through the design parameters (independent variables) of residential buildings and studies the composition and distribution of nitrogen emissions of primary building materials. At the same time, this study uses the data processing and analysis methods of linear regression and ridge regression, and the prediction model of nitrogen emission in the production stage of building materials for residential building design parameters is established.

2. Calculation of nitrogen emission from building materials in residential buildings

2.1. Research object

The research object is determined to be 20 residential buildings with cast-in-situ reinforced concrete shear wall structures in Guangdong, as shown in **Table 1**. The information of 20 north-south residential buildings is described. The energy conservation design of the enclosure structure of all residential buildings is based on the Energy Conservation Design Standard for Residential Buildings in Hot Summer and Warm Winter Areas (JGJ75-2012). The thermal insulation materials are rock boards and glass wool boards; the external windows are plastic steel; and the filler wall is mainly shale bricks.

2.2. Computing method

According to the China Statistical Yearbook, the China Industrial Economic Statistical Yearbook, the China Mining Yearbook, the National Standard Announcement of the People's Republic of China, and other statistical data are used to calculate the nitrogen emission of the building materials involved in this study during the production stage and determine the nitrogen emission factor according to relevant research [18,19]. As the construction year of the research object is only more than ten years, which has not reached the service life, the nitrogen emission of building materials recycled in the demolition phase is not considered in this study.

Table 1. 20 Basic information about residential buildings.

Building number	**Building category**	**Number of elevator households**	**Building area/10,000 m²**	**Floors above ground**	**Floors below ground**	**Building height/m**	**Standard layer area/m²**	**Figure Coefficient**	**Number of rooms on a standard floor**	**Average window-to-floor ratio**	**Building surface area/m²**
1	I	Two elevators and four high-rise buildings	11,474.58	25	2	72.34	325.94	0.28	11	0.11	9919.42
2	I	Two elevators and four high-rise buildings	13,403.50	25	2	72.26	348.02	0.27	12	0.16	10,524.05
3	I	Two elevators and four high-rise buildings	14,410.91	26	2	76.73	348.02	0.27	12	0.17	11,268.97
4	I	Two elevators and four high-rise buildings	14,673.14	26	2	76.73	351.54	0.24	12	0.18	10,718.68
5	II	One elevator, two households, high-risen dependent unit	3242.70	9	2	27.58	248.03	0.30	9	0.16	2713.15
6	II	One elevator, two households, high-rise independent unit	1704.23	9	2	20.73	175.94	0.34	7	0.25	1771.81
7	II	One elevator, two households, high-rise independent unit	3560.11	9	2	27.91	271.78	0.30	9	0.19	2941.85
8	II	One elevator, two households, high-rise independent unit	3518.71	9	2	27.58	268.62	0.29	9	0.23	3095.43
9	II	One elevator, two households, high-rise independent unit	3294.31	10	2	28.23	253.87	0.30	7	0.23	2776.99
10	II	One elevator, two households, high rise, three units, row	7045.77	8	2	25.43	642.10	0.29	21	0.20	5874.99
11	II	One elevator, two households, high rise, three units, row	7512.97	9	2	27.43	627.56	0.28	21	0.24	6268.82
12	II	One elevator, two households, high rise, three units, row	9137.41	9	2	29.28	728.39	0.25	21	0.20	7398.10
13	II	One elevator, two households, high rise, three units, row	3913.15	6	2	19.81	618.38	0.30	20	0.23	3495.65
14	II	One elevator, two households, high rise, three units, row	6246.98	7	2	27.91	628.14	0.31	21	0.25	5340.83
15	II	One elevator, two households, high rise, three units, row	6603.55	7	2	21.79	705.82	0.28	21	0.21	5386.36

Table 1. (*Continued*).

Building number	Building category	Number of elevator households	Building area/10,000 m^2	Floors above ground	Floors below ground	Building height/m	Standard layer area/m^2	Figure Coefficient	Number of rooms on a standard floor	Average window-to-floor ratio	Building surface area/m^2
16	II	One elevator, two households, high rise, three units, row	7298.73	7	2	21.79	720.34	0.24	26	0.23	5359.44
17	II	One elevator, two households, high rise, three units, row	6603.55	7	2	21.79	705.82	0.27	21	0.19	5431.72
18	II	One elevator, two households, high rise, three units, row	6951.14	7	2	21.79	713.08	0.33	21	0.22	6074.98
19	II	One elevator, two households, high rise, three units, row	6772.86	7	2	21.79	674.24	0.34	14	0.24	4559.35
20	II	One elevator, two households, high rise, three units, row	6603.55	7	2	21.79	705.82	0.31	21	0.20	6646.18

3. Calculation results and analysis

3.1. Prediction model research methods

This study calculates the use of primary building materials and nitrogen emissions of each building based on the construction drawings and bill of quantities of 20 residential buildings. At the same time, it completes data cleaning, curve evaluation, linear regression, and ridge regression analysis according to the design parameters of residential buildings in different stages. Finally, it forms the nitrogen emission prediction model of building materials in the production stage.

3.2. Characteristics of building material consumption and nitrogen emission in residential buildings

In this study, according to the density of different building materials, the amount of them is uniformly converted into quality. Among the 20 residential buildings, the average mass of concrete, cement mortar, shale brick, and steel accounted for 79.52%, 10.96%, 5.56%, and 3.66% of the building materials calculated for nitrogen emissions; the total mass of thermal insulation materials and enclosure structures accounted for 0.3%; and the average mass of waterproof coatings, mineral wool decorative acoustic panels, etc. accounted for less than 0.1% of the total mass of all building materials. The building material quality of concrete, cement mortar, shale brick, and steel in the unit building area is 1355.26 kg/m^2, 182.86 kg/m^2, 90.07 kg/m^2, and 66.06 kg/m^2, respectively.

Table 2 analyzes the change in nitrogen emission intensity of different building materials. Because the use positions of building materials in residential buildings differ, nitrogen emission intensity is calculated per-unit building area for all building materials except transparent envelope. In contrast, nitrogen emission intensity is calculated per unit material area for a transparent envelope. It can be seen that the average nitrogen emission intensity of concrete is the highest, about 67.83 kg/m^2; the average nitrogen emission intensity of cement mortar is the second, about 49.20 kg/m^2; the average nitrogen emission intensity of steel and transparent enclosure is the third and fourth, respectively, about 43.09 kg/m^2 and 26.73 kg/m^2; the average nitrogen emission intensity of insulation materials and shale brick is the fifth and sixth, respectively, about 4.90 kg/m^2 and 1.93 kg/m^2.

Table 2. Basic information of 20 residential buildings.

Building number	Shale brick	Concrete	Transparent enclosure	Cement mortar	Thermal insulation materials	Steel products
1	1.42	69.92	17.86	60.03	3.79	26.79
2	0.95	93.08	18.66	50.22	6.07	28.00
3	0.97	61.60	30.52	50.11	4.21	60.78
4	1.01	92.13	22.27	50.84	5.94	33.41
5	1.81	62.71	23.71	47.41	3.83	35.57
6	3.23	63.77	19.60	51.33	4.05	26.40
7	1.65	68.49	19.21	48.39	3.79	28.82
8	2.34	67.66	19.57	70.38	3.91	29.36

Table 2. (*Continued*).

Building number	Shale brick	Concrete	Transparent enclosure	Cement mortar	Thermal insulation materials	Steel products
9	1.54	65.13	30.11	52.24	3.79	45.16
10	2.09	64.04	29.36	53.21	4.81	44.04
11	1.80	62.48	30.32	40.82	4.18	62.48
12	1.72	65.12	30.48	47.57	3.03	66.72
13	3.98	71.74	30.48	81.44	6.02	50.72
14	2.80	64.76	30.50	45.59	5.77	45.75
15	2.40	63.24	30.50	26.98	4.36	45.75
16	1.84	63.18	30.27	42.51	6.50	50.41
17	1.58	65.81	30.05	51.11	6.77	45.08
18	1.94	63.21	30.39	30.74	5.52	45.58
19	1.67	63.97	30.39	44.05	5.90	45.58
20	1.90	64.52	30.28	39.04	5.79	45.42

Generally, the total nitrogen emission of building materials per unit building area of 20 residential buildings is 96.76–156.80 kg/m^2, and the average nitrogen emission is 126.78 kg/m^2. Among them, the proportion of nitrogen emissions from concrete, cement mortar, and steel is large, 36.79%, 30.50%, and 17.02%, respectively, accounting for a total of residential buildings and 84.31% of total nitrogen emission emissions of building materials. The nitrogen emissions of the transparent enclosure, thermal insulation materials, and shale bricks account for 5.00%, 3.59%, and 3.15%, respectively.

It can be seen from the above analysis that the nitrogen emission factor of primary building materials such as concrete, cement mortar, and steel is high, and the consumption of concrete, cement mortar, and steel in residential buildings with reinforced concrete shear wall structures is very large. Therefore, for residential buildings to apply for green building evaluation marks, the space scale of residential buildings must be considered in the civil engineering industry. Reduce the waste of building materials. At the same time, the durability and recycling of building materials must be considered to reduce the maintenance and replacement of building materials. Moreover, due to the high thermal performance requirements of thermal insulation materials and transparent enclosures, thermal insulation materials and transparent enclosures with low nitrogen emission factors must be considered in the civil engineering industry.

3.3. Design parameters and nitrogen emission of building materials

For residential buildings, the factors that affect the total nitrogen emissions of building materials mainly include the shape, number, and distribution of each space inside the building. From the architectural design perspective, the shape and quantity include the design parameters such as the total building area, building cover area, building surface area, and the total height of the building. number of floors, etc. The design parameters for the distribution of various spaces inside the building include the number and corresponding area of various functional rooms on the standard floor.

Considering the above factors, based on the essential information in **Table 1**, this study supplements the basic parameters of residential building design. It refines the analysis parameters used to describe the nitrogen emissions of building materials. Then, using SPSS software, the correlation analysis is conducted on 24 basic parameters of residential building design and 15 analysis parameters describing the nitrogen emissions of building materials, as shown in **Table 3** and **Figure 1**. Then, nitrogen emission prediction models based on different design parameters are established using the following two prediction methods. The two prediction methods are respectively: the first one is house type design parameters, namely, the shape and quantity of buildings, the distribution of each space inside buildings, house type functions, and other parameters; the second one is building material parameters, namely, the amount of concrete, cement mortar, steel, transparent enclosure, and other building materials.

Table 3. 24 parameters for residential building design and 15 parameters for describing nitrogen emission from building materials.

Number	Parameters for residential building design	Number	Parameters for residential building design (A20–A24) Parameters for describing nitrogen emission (A25–A39)
A0	Number of floors above ground	A20	Total number of rooms in public areas
A1	Number of floors below ground	A21	Standard layer width
A2	Number of standard stairs	A22	Standard layer depth
A3	Number of standard floor households	A23	Perimeter of standard layer
A4	Total number of households	A24	Average window wall ratio
A5	Total building area	A25	Total nitrogen emission intensity of building materials
A6	Standard floor area	A26	Total nitrogen emission building materials
A7	Building surface area	A27	Nitrogen emission of shale brick
A8	Figure coefficient	A28	Nitrogen emission intensity of shale brick
A9	Number of bedrooms on standard floor	A29	Nitrogen emission concrete
A10	Total number of bedrooms	A30	Nitrogen emission intensity of concrete
A11	Number of toilets on a standard floor	A31	Nitrogen emission from steel
A12	Total number of toilets	A32	Nitrogen emission intensity of steel
A13	Number of rooms on a standard floor	A33	Nitrogen emission of cement mortar
A14	Total rooms	A34	Nitrogen emission strength of cement mortar
A15	Number of main functional rooms on the standard floor	A35	Nitrogen emission from insulation materials
A16	Total number of main functional rooms	A36	Nitrogen emission intensity of insulation materials
A17	Number of indoor rooms on a standard floor	A37	Nitrogen emission of transparent enclosure
A18	Total number of indoor rooms	A38	Nitrogen emission intensity of transparent enclosure 1
A19	Number of rooms in the public area of the standard floor	A39	Nitrogen emission intensity of transparent enclosure 2

Note: A38 and A39 in **Table 3** are nitrogen emissions per unit building area and nitrogen emissions per unit material area, respectively.

Figure 1 shows that the separators have four kinds of correlations: extremely significant positive correlation 0.95, significant positive correlation 0.90–0.95, positive correlation 0.85–0.90, and negative correlation.

A1	0.12																																						
A2	-0.54	0.10																																					
A3	-0.70	0.10	1.00**																																				
A4	0.36	0.16	0.39	0.43																																			
A5	0.37	0.18	0.39	0.42	0.98**																																		
A6	-0.44	0.31	0.93**	0.93**	0.43	0.46																																	
A7	0.37	0.18	0.39	0.42	0.99**	0.97**	0.41																																
A8	0.14	-0.52	-0.48	-0.51	-0.29	-0.37	-0.67	-0.27																															
A9	-0.48	0.19	0.97**	0.97**	0.38	0.41	0.96**	0.36	-0.56																														
A10	0.39	0.18	0.40	0.42	0.98**	0.99**	0.46	0.96**	-0.35	0.44																													
A11	-0.52	0.16	0.99**	0.99**	0.42	0.41	0.94**	0.41	-0.51	0.97**	0.41																												
A12	0.41	0.17	0.42	0.43	1.00**	0.98**	0.44	0.99**	-0.29	0.41	0.99**	0.43																											
A13	-0.36	0.26	0.93**	0.94**	0.44*	0.44*	0.94**	0.43*	-0.75	0.93*	0.44*	0.93**	0.44*																										
A14	0.37	0.18	0.39	0.42	0.99**	0.98**	0.42	0.97**	-0.33	0.38	0.97**	0.40	0.99**	0.48																									
A15	-0.53	0.20	0.97**	0.97**	0.40	0.43	0.95**	0.38	-0.59	1.00**	0.44	0.97**	0.40	0.93**	0.52*																								
A16	0.37	0.18	0.39	0.42	0.98**	1.00**	0.45	0.96**	-0.33	0.43	1.00**	0.40	0.98**	0.46	0.97**	0.43																							
A17	-0.43	0.28	0.94*	0.94**	0.46	0.47*	0.93**	0.45	-0.03	0.93**	0.46	0.93**	0.46	0.99**	0.51*	0.93**	0.46																						
A18	0.36	0.17	0.38	0.42	0.99**	0.98**	0.41	0.97**	-0.33	0.39	0.97**	0.39	0.99**	0.47	1.00**	0.37	0.97**	0.46*																					
A19	0.30	0.02	0.48*	0.50*	0.94*	0.93*	0.51*	0.93*	-0.32	0.46	0.93*	0.48	0.94*	0.53	0.93*	0.46	0.93*	0.49	0.93*																				
A20	0.39	0.18	0.40	0.42	0.99**	0.98**	0.43	0.97**	-0.34	0.39	0.97**	0.41	0.99**	0.49	1.00**	0.39	0.97**	0.48*	1.00*	0.93*																			
A21	-0.56	0.26	0.94*	0.94*	0.52	0.42	0.97**	0.40	-0.72	0.95**	0.42	0.94*	0.39	0.91*	0.40	0.95**	0.41	0.91*	0.40	0.48*	0.40																		
A22	0.17	-0.14	0.41	0.46	0.69*	0.67	0.43	0.71*	-0.17	0.33	0.65	0.39	0.69*	0.40	0.66*	0.33	0.66	0.36	0.67	0.78	0.67	0.43																	
A23	-0.45	0.20	0.93*	0.93*	38.13	0.39	0.96**	0.39	-0.55	0.91*	0.39	0.93*	0.38	0.91*	0.39	0.90*	0.39	0.84	0.39	0.48	0.39	0.97**	0.49																
A24	-0.45	-0.11	0.14	0.15	-0.36	-0.37	0.07	-0.36	0.04	0.11	-0.38	0.11	-0.36	0.10	-0.34	0.11	-0.37	0.11	-0.34	-0.31	-0.34	0.03	-0.32	0.05															
A25	-0.11	-0.56	-0.13	-0.14	-0.28	-0.32	-0.25	-0.20	0.33	-0.24	-0.33	-0.17	-0.28	-0.15	-0.25	-0.24	-0.33	-0.16	-0.25	-0.17	-0.25	-0.22	0.04	-0.13	0.14														
A26	0.39	0.18	0.40	0.42	0.98**	0.98**	0.45	0.99**	-0.34	0.40	0.97**	0.41	0.98**	0.48	0.99**	0.40	0.97**	0.48	0.99**	0.88	0.99**	0.41	0.73	0.41	-0.35	-0.21													
A27	-0.15	-0.15	0.62*	0.69*	0.54*	0.50*	0.55*	0.53	-0.08	0.56	0.51	0.63	0.55	0.49	0.48	0.56	0.52	0.47	0.48	0.62	0.48	0.54	0.57	0.56	-0.01	-0.10	0.48												
A28	-0.72	-0.30	0.24	0.25	-0.59	-0.59	0.12	-0.59	0.11	0.21	-0.57	0.20	-0.59	0.05	-0.61	0.21	-0.58	0.07	-0.61	-0.47	-0.61	0.13	-0.34	0.12	0.61	0.24	-0.61	0.13											
A29	0.37	0.18	0.40	0.42	0.97**	0.98**	0.47	0.97**	-0.35	0.41	0.96**	0.41	0.97**	0.48	0.97**	0.41	0.97**	0.47	0.97**	0.93*	0.97**	0.44	0.75	0.44	-0.41	-0.24	0.99**	0.48	-0.64										
A30	0.14	-0.61	-0.10	-0.10	0.11	0.10	-0.17	0.16	0.27	-0.20	0.06	-0.15	0.11	-0.15	0.13	-0.20	0.07	-0.16	0.13	0.25	0.13	-0.10	0.05	-0.03	-0.15	0.65	0.17	0.00	-0.18	0.21									
A31	0.35	0.17	0.38	0.42	0.98**	0.99**	0.43	0.97**	-0.33	0.40	0.99**	0.39	0.98**	0.46	0.99**	0.40	0.98**	0.53	0.99**	0.93*	0.99**	0.38	0.66	0.38	-0.31	-0.25	0.99**	0.49	-0.56	0.98**	0.11								
A32	0.19	-0.59	-0.31	0.33	-0.01	-0.01	-0.44	0.05	0.51	-0.36	-0.03	-0.35	-0.01	-0.40	0.00	-0.36	-0.03	-0.39	0.00	0.03	0.00	-0.41	0.08	-0.38	0.20	0.60	0.04	0.02	0.05	0.00	0.59	0.03							
A33	0.40	0.09	0.37	0.39	0.95**	0.94*	0.39	0.97**	-0.26	-0.37	0.93*	0.38	0.96**	0.45	0.97**	-0.37	0.94*	0.44	0.97**	0.93*	0.97**	0.36	0.72	0.38	-0.40	-0.07	0.97**	0.52	-0.60	0.97**	0.23	0.97**	0.12						
A34	0.39	-0.50	-0.33	-0.35	-0.37	-0.40	-0.46	-0.33	0.38	-0.40	-0.41	-0.33	-0.37	-0.33	-0.33	-0.40	-0.41	-0.33	-0.33	-0.32	-0.33	-0.40	-0.20	-0.33	-0.07	0.87*	-0.33	-0.21	0.15	-0.35	0.44	-0.36	0.49	-0.16					
A35	0.28	0.15	0.49	0.52	0.91*	0.93*	0.54	0.93*	-0.41	0.49	0.93*	0.49	0.93*	0.57	0.93*	0.49	0.93*	0.55	0.93*	0.93*	0.93*	0.49	0.75	0.53	-0.36	-0.21	0.93*	0.48	-0.49	0.93*	0.17	0.93*	-0.11	0.85	-0.35				
A36	-0.37	-0.15	0.34	0.37	-0.16	-0.13	0.30	-0.13	-0.33	0.31	-0.15	0.31	-0.16	0.36	-0.15	0.31	-0.15	0.35	-0.15	-0.07	-0.15	0.31	0.09	0.33	0.12	0.30	-0.11	-0.05	0.38	-0.12	0.14	-0.14	-0.15	-0.11	0.15	0.16			
A37	0.31	0.44	0.41	0.44	0.87*	0.89*	0.50	0.90*	-0.48	0.45	0.90*	0.42	0.81	0.55	0.93*	0.45	0.82	0.54	0.93*	0.73	0.93*	0.41	0.49	0.41	-0.09	-0.35	0.83	0.36	-0.50	0.80	-0.12	0.93*	-0.11	0.77	-0.49	0.77	-0.09		
A38	0.01	0.24	-0.21	-0.22	-0.31	-0.31	-0.15	-0.29	-0.13	-0.22	-0.34	-0.22	-0.31	-0.04	-0.25	-0.22	-0.33	-0.05	-0.25	-0.34	-0.25	-0.27	-0.43	-0.24	0.65	0.16	-0.26	-0.36	0.18	-0.34	-0.26	-0.25	0.10	-0.29	0.06	-0.33	0.08	0.08	
A39	-0.08	0.47	0.00	-0.00	-0.22	-0.18	0.16	-0.25	-0.56	0.06	-0.18	0.03	-0.22	0.22	-0.15	0.06	-0.19	0.21	-0.15	-0.18	-0.15	0.08	-0.32	0.06	0.11	-0.14	-0.16	-0.35	-0.01	-0.18	-0.39	-0.16	-0.46	-0.21	-0.09	-0.16	0.15	0.15	0.52
	A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24	A25	A26	A27	A28	A29	A30	A31	A32	A33	A34	A35	A36	A37	A38

Figure 1. The analysis chart of the correlation between the design parameters of residential buildings and the nitrogen emission of building materials.

Among them, (1) The parameters with extremely significant positive correlation are:

Total nitrogen emission of building materials (A26) and total number of households (A4), total building area (A5), building surface area (A7), total number of bedrooms (A10), total number of toilets (A12), total number of rooms (A14), total number of main functional rooms (A1 6), total number of indoor rooms (A18), total number of rooms in public areas (A20), concrete nitrogen emission (A29) Between steel nitrogen emission (A31) and cement mortar nitrogen emission (A33), 2) concrete nitrogen emission (A29) and total number of households (A4), total building area (A5), building surface area (A7), total number of bedrooms (A10), total number of toilets (A1 2), total number of rooms (A14), total number of main functional rooms (A1 6), total number of indoor rooms (A18) Between the total number of rooms in the public area of residential buildings (A20), steel nitrogen emissions (A31), and cement mortar nitrogen emissions (A33), 3) between steel nitrogen emissions (A31) and the total number of households (A4), total building area (A5), and building surface area(A7), total number of bedrooms in residential buildings (A10), total number of toilets in residential buildings (A12), total number of rooms in residential buildings (A14), total number of main functional rooms in residential buildings (A16), total number of indoor rooms in residential buildings (A18), total number of rooms in public areas in residential buildings (A20), cement mortar nitrogen emissions (A33), 4) cement mortar nitrogen emissions (A33) and total number of households (A4),building surface area (A7) Total number of toilets in residential buildings (A12), total number of rooms in residential buildings (A14), total number of rooms in residential buildings (A18), and total number of rooms in public areas in residential buildings (A20).

(2) The parameters with significant positive correlation are: 1) the total nitrogen emissions of building materials (A26) and the number of rooms in the public area of the standard floor (A19), the nitrogen emissions of insulation materials (A35), 2) the nitrogen emissions of steel (A31) and the number of rooms in the public area of the standard floor (A19), the nitrogen emissions of insulation materials (A35), the nitrogen emissions of transparent enclosures (A37), 3) the nitrogen emissions of cement mortar (A33) and the total building area (A5) Between the total number of bedrooms in residential buildings (A10), the total number of main functional rooms in residential buildings (A16), and the number of rooms in public areas of standard floors (A19), 4) the nitrogen emission of insulation materials (A35) and the total number of households (A4), the total building area (A5), the building surface area (A7), the total number of residential buildings (A12), the total number of rooms in residential buildings (A1 4) Between the total number of main functional rooms (A16), the total number of indoor rooms (A1 8), the number of rooms in the public area of the standard floor (A1 9), the total number of rooms in the public area of the residential building (A20), and the concrete nitrogen emissions (A29), 5) the nitrogen emissions of the transparent enclosure (A37) and the total number of rooms in the residential building (A14), the total number of indoor rooms in the residential building (A18), and the total number of rooms in the public area of the residential building (A20).

(3) The parameters with negative correlation are: 1) between shape coefficient (A8) and other design parameters, 2) between average window wall ratio (A24) and other design parameters, 3) between nitrogen emission intensity of transparent

enclosures (A38, A39) and other design parameters; 4) between total nitrogen emission intensity of building materials (A25) and other design parameters; 5) between nitrogen emission intensity of shale bricks (A28) and other design parameters. 6) Between the nitrogen emission strength of cement mortar (A34) and other design parameters, and between the nitrogen emission strength of insulation materials (A36) and other design parameters.

To sum up, the increase in building volume will reduce the shape coefficient of residential buildings but, at the same time, increase the total building area of residential buildings, so the total nitrogen emission of building materials will increase. In contrast, the total nitrogen emission intensity of building materials will decrease. At the same time, because the consumption of building materials and nitrogen emissions of transparent enclosure structures account for a small proportion, the average window wall ratio has a limited impact on the total nitrogen emissions of building materials. In addition, the nitrogen emission intensity is directly proportional to the nitrogen emission coefficient. Compared with the total nitrogen emission of building materials, the nitrogen emission intensity of building materials is not closely related to the design parameters of residential buildings, which is insufficient to provide a practical reference for the low nitrogen design of residential buildings.

4. Prediction model and validation of nitrogen emission from building materials

4.1. Prediction model of total nitrogen emissions of building materials-prediction based on house-type design parameters

In this study, the relationship between 12 highly significant positive correlation parameters and the total nitrogen emissions of building materials was conducted in linear, logistic, and quadratic terms (4 of the 12 design parameters are selected as representatives in **Figure 2**). The results show that the design parameters have a significant linear relationship with the total nitrogen emissions of building materials, which can be directly used to build a linear regression model.

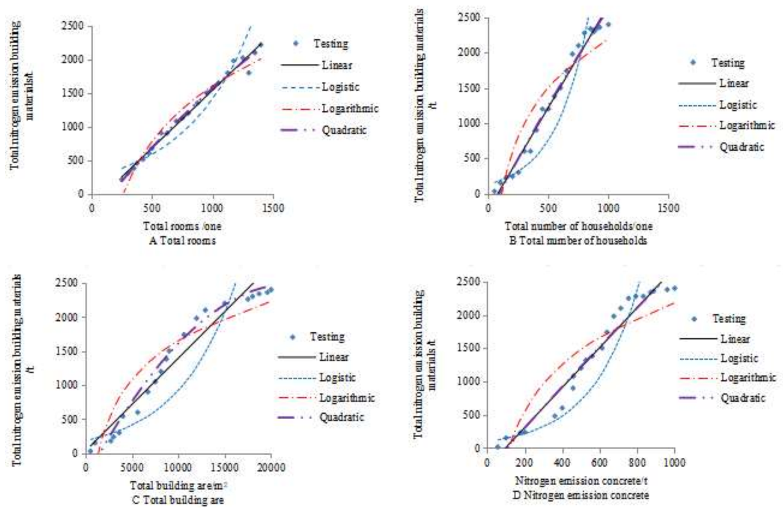


Figure 2. The curve evaluation results between design parameters of residential buildings and total nitrogen emission of building materials.

The rooms on the standard floor of the residential building include the main functional rooms (bedroom and living room) and the secondary functional rooms (such as toilets, kitchens, and staircases). In the design of residential buildings, the living room and dining room can be combined and designed with the number of households equivalent to the standard floor, so the total number of main functional rooms of residential buildings is equal to the product of "the number of floors above the ground of residential buildings" and "the sum of the number of bedrooms on the standard floor and the number of households on the standard floor." At the same time, because the window-to-floor ratio of residential buildings is variable, the exterior area of residential buildings changes in a particular range, and the value is not unique. Therefore, this study uses other parameters of residential building design to evaluate the exterior area of residential buildings.

According to the curve fitting in **Figure 3**, the combined variable based on the width and depth of the standard floor and the number of floors above the ground of the residential building, as well as the quadratic curve of the combined variable, can describe the exterior area of the residential building, and its linear and nonlinear equations can be substituted into the fitting process of the prediction model of total nitrogen emissions of building materials. To further refine the main design parameters that affect the nitrogen emissions of building materials in the process of fitting the prediction model of total nitrogen emissions of building materials, this study uses an advanced method to remove insignificant independent variables and uses a ridge regression model to reconstruct the design parameters with collinearity characteristics.

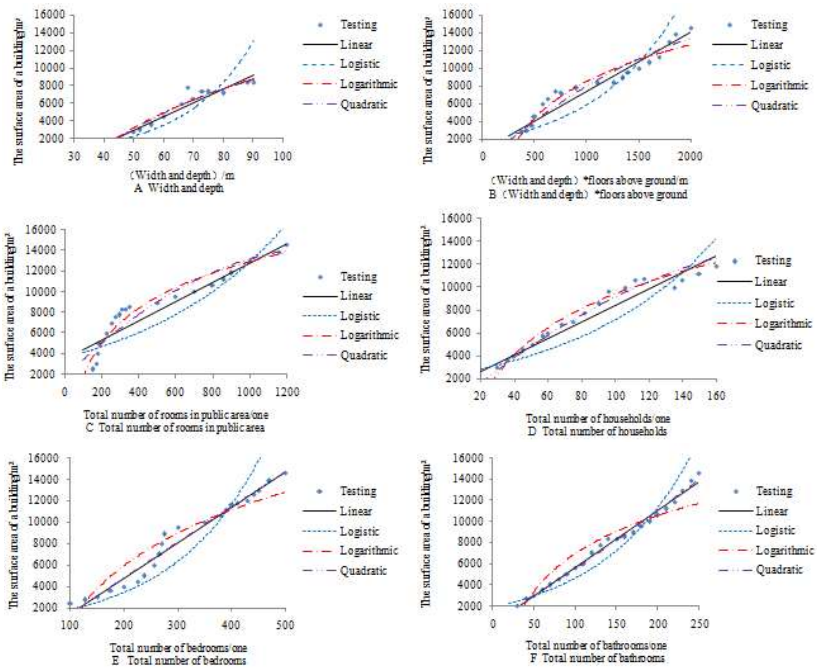


Figure 3. The curve evaluation result of residential building design parameters and exterior surface area.

In this study, Equations (1)–(6) represents the establishment of a prediction model for the total nitrogen emissions of six building materials (based on the design parameters of the house type):

$$G1 = 396.90 * S + 179{,}617.37 \quad (1)$$

$$G2 = 0.82 * (N1 + N2)^2 * (w + d)^2 + 5550.26 * (N1 + N2) * (w + d) - 832{,}949.88 \quad (2)$$

$$G3 = 3451.96 * (N1 + N2) * (w + d) + 9632.11 * (w + d) - 474{,}303.08 \quad (3)$$

$$G4 = 2293.79 * (N1 + N2) * (w + d) + 9916.80 * (w + d) + 5450.36 * N3 * N1 - 313{,}796.61 \quad (4)$$

$$G5 = 2096.76 * (N1 + N2) * (w + d) + 9985.25 * (w + d) + 4562.21 * N4 * N1 - 279{,}195.76 \quad (5)$$

$$G6 = 3533.96 * (N1 + N2) * (w + d) + 12{,}350.15 * N5 - 3633.50.76 \quad (6)$$

S is the total building area (m^2), w and d are the face width and depth (m) of the standard floor, $N1$ and $N2$ are, respectively, the number of floors above and below the ground of the residential building, $N3$, $N4$, and $N5$ are respectively the number of bedrooms, rooms with main functions, and the total number of rooms in the standard floor of the residential building, and $G1$ to $G6$ are the total nitrogen emissions in the production stage of building materials of models M1 to M6 (kg).

M1 to M6 are built based on house-type design process parameters (**Table 4**). M1 is a model based on the total area of residential buildings as a variable, which can only be applied to the total nitrogen emissions of building materials in the planning stage of residential building projects. M2 to M6 use multiple combined variables to replace the surface area of buildings. Combination variables of M2 to M6 are based on the internal space scale of residential buildings (including the number of bedrooms on the standard floor, the number of main functional rooms, and the total number of rooms). Except for M1, the adjusted R^2 is greater than or equal to 0.986, which is a good fit. Therefore, the project planning, scheme design, preliminary expansion design, detailed design, and other processes of this residential building can provide a reference for low nitrogen emissions of residential buildings.

Table 4. The fitting of the model for predicting the total nitrogen emission of building materials-the prediction according to the parameters of household design.

Model	Variable	Construction method	Adjusted R^2
M1	S	Linear regression	0.916
M2	$N1$, $N2$, w, d	Nonlinear regression	0.986
M3	$N1$, $N2$, w, d	Linear regression	0.989
M4	$N1$, $N2$, w, d, $N3$	Ridge regression $K = 0.008$	0.989
M5	$N1$, $N2$, w, d, $N4$	Ridge regression $K = 0.008$	0.989
M6	$N1$, $N2$, w, d, $N5$	Linear regression	0.987

4.2. Indirect prediction model of total nitrogen emissions from building materials

The total nitrogen emission of concrete, cement mortar, steel, and transparent enclosure structures accounts for 89.31% of the total nitrogen emission of building materials. According to the significance of design parameters and the degree of optimization of model fitting, regression models of nitrogen emissions from concrete (Mh1 and Mh2), steel (Mg1 and Mg2), and cement mortar (Mss) are established, respectively. Mc1 and Mc2 are represented by Equations (7) and (8), Ms1 and Ms2 are represented by Equations (9) and (10), and Mass is represented by Equation (11):

$$\text{Gh1} = 1385.30 * (N1 + N2) * (w + d) + 3980.80 * (w + d) - 242{,}373.03 \quad (7)$$

$$\text{GGh2} = 1401.30 \times (N1 + N2) * (w + d) + 116{,}03.86 * N4 - 193{,}878.00 \quad (8)$$

$$\text{Gg1} = 715.39 \times (N1 + N2) * (w + d) - 48{,}019.30 \quad (9)$$

$$\text{Gg2} = 363.80 * (N1 + N2) * (w + d) + 1197.95 * N5 * N1 + 5087.86 \quad (10)$$

$$\text{Gss} = 1085.28 * (N1 + N2) * (w + d) + 21{,}755.86 \quad (11)$$

Gh1, Gh2, Gg1, Gg2, and Gss represent the nitrogen emissions (kg) in the corresponding building material production stage. At the same time, this study builds an aggression model (Mt) for nitrogen emissions of transparent enclosures based on the perimeter of standard floors, number of floors above ground, and average window wall ratio of residential buildings:

$$Gt = 107.86 * Sc + 21{,}282.16 \quad (12)$$

$$Sc = 3.26 * [2.96 * (w + d) - 20.50] * N1 * Q - 39.16 \quad (13)$$

Gt is the nitrogen emission in the production phase of transparent enclosures (kg), *Sc* is the total area of windows in residential buildings (m^2), and *Q* is the average window wall ratio.

It can be seen from **Table 5** that Equations (14)–(17) represent the establishment of a prediction model for total nitrogen emissions of four building materials (based on the prediction of building material parameters):

$$G7 = \frac{\text{Gh1} + \text{Gg1} + \text{Gss}}{90.90\%} + Gt \quad (14)$$

$$G8 = \frac{\text{Gh1} + \text{Gg2} + \text{Gss}}{90.90\%} + Gt \quad (15)$$

$$G9 = \frac{\text{Gh2} + \text{Gg1} + \text{Gss}}{90.90\%} + Gt \quad (16)$$

$$G10 = \frac{\text{Gh2} + \text{Gg2} + \text{Gss}}{90.90\%} + Gt \quad (17)$$

The above prediction model estimates the total nitrogen emission of building materials through concrete, steel, cement mortar, and transparent enclosure structures. This may reduce the fitting accuracy to a certain extent but can significantly reflect the nitrogen emission distribution and change the characteristics of the primary building materials.

Table 5. Prediction model of total nitrogen emission from building materials and the fitting of the combination part-prediction according to the parameters of building materials.

Model	Variable	Construction method	Adjusted R^2
Mh1	*N*1, *N*2, *w*, *d*	Linear regression	0.996
Mh2	*N*1, *N*2, *w*, *d*, *N*5	Linear regression	0.996
Mg1	*N*1, *N*2, *w*, *d*	Linear regression	0.991
Mg2	*N*1, *N*2, *w*, *d*, *N*5	Ridge regression = 0.006	0.993
Mss	*N*1, *N*2, *w*, *d*	Linear regression	0.956
Mt	*N*1, *w*, *d*, *Q*	Linear regression	0.88
M7	Mh1, Mg1, Mss, Mt	Combination	0.986
M8	Mh1, Mg2, Mss, Mt	Combination	0.987
M9	Mh2, Mg1, Mss, Mt	Combination	0.986
M10	Mh2, Mg2, Mss, Mt	Combination	0.987

According to the above analysis, 10 models can fit the total nitrogen emissions of building materials in 20 residential buildings well (**Figure 4**). In contrast, since M1 has only one independent variable and is only based on the total building area, M2 is a nonlinear model established based on spatial shape parameters. The fitting effect of these two models is not as good as that of the other 8 models; M3–M5 requires a few independent variables, which can be used in different stages of architectural design. Compared with the other nine models, M6 has the most minor errors but requires the most independent variables, so it requires very high depth for architectural design.

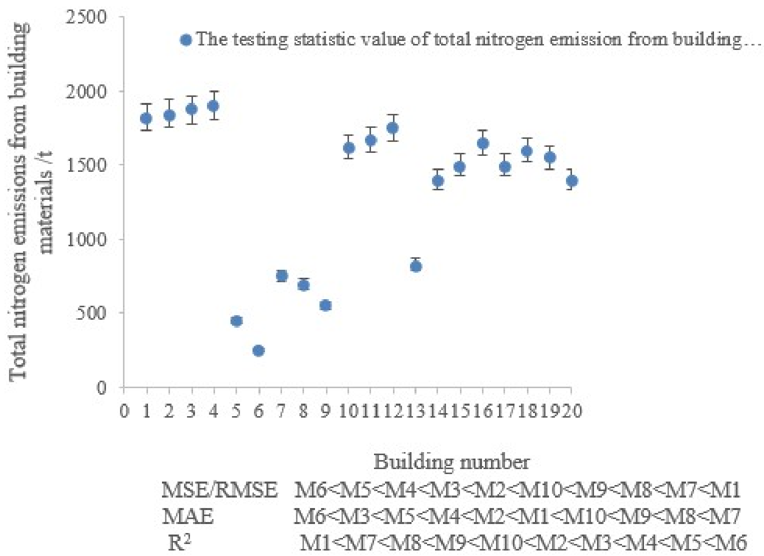


Figure 4. The fitting effect of the regression model.

4.3. Model validation of total nitrogen emissions from building materials

Based on selecting 20 residential buildings, this study selects 5 additional residential buildings (see **Table 6**); the prediction performance of the 10 models was analyzed from the following four aspects: mean square error MSE, root mean square error RMSE, mean absolute error MAE, and prediction goodness R^2.

Table 6. 5 validates design information of residential buildings and total nitrogen emissions from building materials.

Building number	S/m^2	$N1$	$N2$	w/m	d/m	Q	$N3$	$N4$	$N5$	Total nitrogen emissions from building materials/kg
21	9460.8	15	2	38.59	12.50	0.20	10	14	34	1,239,716.4
22	10,858.5	16	3	32.078	15.48	0.17	10	17	43	1,296,906.2
23	10,152.1	22	3	24.596	14.53	0.16	8	13	33.54	1,161,517.9
24	7386.4	20	2	20.4	14.96	0.20	7	9	22.95	821,896.17
25	14,356.1	21	2	42.0993	15.31	0.21	12	17	46.98	1,554,730.8

The verification results are shown in **Table 7** and **Figure 5**. It can be seen from the verification results of M1 and M2 that the prediction performance of M1 and M2 is poor, which indicates that only the total building area and spatial shape parameters of residential buildings cannot accurately provide practical guidance for the low nitrogen design of residential buildings. It can be seen from the verification results of M4 that the prediction performance of M4 is not ideal. This indicates that the total nitrogen emission of building materials cannot be accurately predicted through the internal space scale of residential buildings and the number of standard bedrooms in each building. It can be seen from the verification results of M3 and M5 that the error of M3 and M5 is low, and the prediction performance is good, which indicates that the spatial shape and internal spatial scale of residential buildings can be used to predict the total nitrogen emissions of building materials. It can be seen from the verification results of M6 that the error of M6 is the lowest. With the deepening of the conceptual design of residential buildings, M6 can provide the most ideal data support for the optimal design of residential buildings. At the same time, the prediction level from M7 to M10 is similar, so nitrogen emission of the primary building materials used can be targeted and analyzed in combination with the internal space design of residential buildings.

Table 7. 10 predictive performances of models.

Model	MSE	RMSE	MAE	R^2
M1	279,586.51	518.07	471.45	0.71
M2	297,587.44	537.27	400.67	0.76
M3	196,867.92	433.68	373.92	0.88
M4	207,197.58	434.31	382.98	0.80
M5	166,531.35	399.84	341.79	0.90
M6	181,954.79	420.12	365.28	0.96
M7	216,216.22	446.57	405.38	0.79
M8	211,772.69	457.15	405.45	0.78
M9	219,956.42	452.38	405.12	0.77
M10	210,976.31	462.46	405.75	0.78

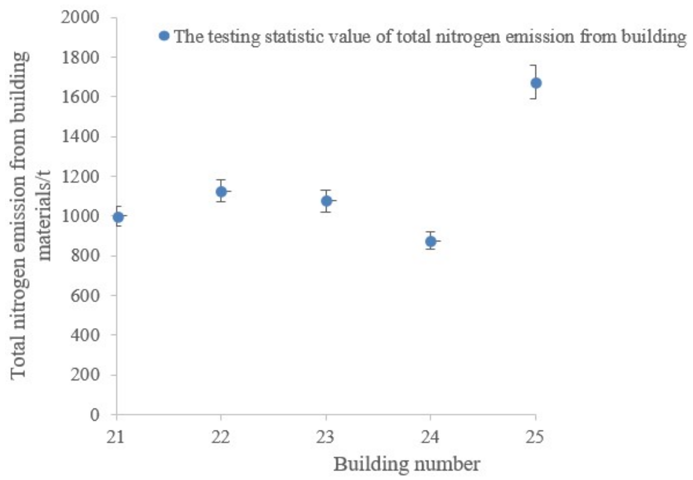


Figure 5. Model predictive performance validation based on 5 residential buildings.

5. Improvement for future research

Lifecycle Assessment: Expand the analysis to encompass nitrogen emissions from all lifecycle stages of building materials. This would offer a more holistic view of the environmental impact and better guide sustainable building practices.

Broaden Geographic Scope: Conduct similar studies in different regions to validate the findings and increase their generalization. This would help in understanding regional variations in building practices and environmental conditions.

Complexity of Models: While the regression models are statistically sound, their practical implementation may require specialized knowledge. Simplifying these models or providing user-friendly tools could enhance their usability for industry practitioners.

6. Conclusions

In this study, 20 residential buildings with cast-in-reinforcement concrete shear wall structures were taken as examples to analyze the total nitrogen emissions of building materials in the production process. The research shows that the proportion of nitrogen emissions from concrete, cement mortar, steel, and transparent enclosure structures accounts for 89.31% of the total nitrogen emissions from building materials. Although the nitrogen emission factor of concrete, cement mortar, and steel is low due to the large number of materials used in the overall construction process, to reduce the nitrogen emission, the shape and volume of buildings and the division form of internal space structure must be accurate in the design process. Using building materials with the best durability should be considered to maximize recycling of building materials. For a transparent enclosure structure, it is necessary to reasonably select low-nitrogen emission building materials based on green building design specifications and standards.

In this study, nitrogen emission prediction models based on different design parameters are established according to the following two prediction methods (house type design parameters and building material parameters), and 10 kinds of nitrogen emission prediction models are established and verified through the design parameters of different residential buildings. These 10 models can provide a reference for low nitrogen emissions of residential buildings in different stages of project planning, scheme design, preliminary expansion design, and deepening design of residential buildings. Among them, the prediction levels from M7 to M10 are similar, and the nitrogen emission of the primary building materials used can be targeted based on the internal space design of residential buildings. The linear model M1, based on the total building area, and the nonlinear model M2, based on the number of floors above and below ground, surface width, and depth, have poor prediction performance and significant errors. The prediction performance of the ridge regression model M4 based on the number of floors above and below ground, the width and depth of the area, and the total number of bedrooms is not ideal. Linear model M3 based on the number of floors above and below ground, face width, and depth, and ridge regression model M5 based on the number of floors above and below ground, face width and depth, and the total number of main functional rooms have good fitting and prediction performance. The linear regression model M6, based on the number of floors above and below ground, the width and depth of the area, and the total number of rooms, has the best fitting and prediction performance. M3, M5, and M6 can accurately predict the nitrogen emission composition and distribution characteristics of building materials in residential building design and lay a foundation for future research on nitrogen emission evaluation and calculation methods and nitrogen emission reduction technology strategies.

Conflict of interest: The author declares no conflict of interest.

References

1. Malik A, Oita A, Shaw E, et al. Drivers of global nitrogen emissions. Environmental Research Letters. 2022; 17(1): 015006. doi: 10.1088/1748-9326/ac413c
2. Wu JX, Zhou K, Liu HC. Driving effect and spatial interaction characteristics of urbanization process on ammonia nitrogen emissions - taking the Yangtze River Delta as an example. Journal of Environmental Science. 2021; 41(10): 3893-3904. doi: 10.13671/j.hjkxxb.2021.0280
3. Wu HX, Cai J, Ren QQ, et al. Experimental Investigation of Cutting Nitrogen Oxides Emission from Cement Kilns Using Coal Preheating Method. Journal of Thermal Science. 2021; 30(04): 1097-1107. doi: 10.13671/j.hjkxxb.2021.0280
4. Liu YQ, Yan FH, Zheng LM, et al. Nitrogen emission dry deposition transport process of typical urban agglomerations based on “centric” migration Research. Journal of Environmental Science. 2021; 41(08): 3051-3060. doi: 10.13671/j.hjkxxb.2020.0555
5. McCourt S, MacDonald GK. Provincial nitrogen footprints highlight variability in drivers of reactive nitrogen emissions in Canada. Environmental Research Letters. 2021; 16(9): 095007. doi: 10.1088/1748-9326/ac1e3b
6. Jiang L, He SX, Cui YZ. Analysis of NO_x emission drivers based on spatial econometric model: based on satellite observation data. Geographic Science. 2020; 40(3): 364-373. doi: 10.13249/j.cnki.sgs.2020.03.004
7. Pan Y, Gu M, He Y, et al. Revisiting the Concentration Observations and Source Apportionment of Atmospheric Ammonia. Advances in Atmospheric Sciences. 2020; 37(9): 933-938. doi: 10.1007/s00376-020-2111-2
8. Xian CF, Pan XL, Zhen Q, et al. Comprehensive Assessment of Pollution Nitrogen Footprint and Ash Water Footprint of Urban Ecosystem. Environmental Science Journal. 2019; 3: 985-995. doi: 10.13671/j.hjkxxb.2018.0451
9. Cai X, Hu X, Zheng L, et al. Redistribution of C and N Atoms in High Nitrogen Martensitic Stainless Steel During Cryogenic Treatment. Acta Metallurgica Sinica (English Letters). 2021; 35(4): 591-595. doi: 10.1007/s40195-021-01265-7
10. Shan L, Ren W. Discussion on methods affecting the accuracy of determination of oxygen and nitrogen contenting steel. Hot Working Process. 2021; 50(24): 74-76. doi: 10.14158/j.cnki.1001-3814.20183727
11. Shen HY, Wang MY, Zhang N, et al. Automatic detection method of NO_x pollutant concentration under building application of photocatalytic materials. Automation and Instrumentation. 2021; 6: 18-21.
12. Li X, Liu J, Zheng C, et al. Detection and analysis of nitriteion mass concentration in concrete(Chinese). Journal of Shenyang Jianzhu University (Natural Science Edition). 2018; 34(2): 303-309. doi: 10.11717/j.issn:2095-1922.2018.02.13
13. Tang XC. Control technology and application of flue gas nitrogen oxides in cement industry. Cement Engineering. 2020; 4: 76-77, 83.
14. Zhao DH. Analysis of NO_x control technology in cement industry. Cement Technology. 2020; 5: 24-27.
15. Ma XQ, Gao XD, Fan YB, et al. Nitrogen oxide treatment and ammonia emission in domestic cement industry. China Cement. 2019; 5: 78-80.
16. Zhu S. Research on Ways and Measures to Reduce NO_x Emission in Iron and Steel Enterprises. Environment and Development. 2018; 30(10): 120, 122.
17. Yao ZH, Zhang L, Du J. Research on Prevention and Control of Nitrogen Oxide Pollution in Iron and Steel Industry. Environmental Science and Management. 2015; 40(3): 71-74.
18. Zhang CY, Wang SX, Xing J, et al. Analysis on the current situation and development trend of China’s energy related nitrogen oxide emissions. Environmental Science Journal. 2008; 12: 2470-2479. doi: 10.13671/j.hjkxxb.2008.12.026
19. Li JM, Li GD. Present situation and countermeasures of nitrogen oxides emissions in Chinese cement industry. Applied Chemical Industry. 2013; 42(9): 1687-1689. doi: 10.16581/j.cnki.issn1671-3206.2013.09.018

Building Engineering 2024, 2(2), 1567.
https://doi.org/10.59400/be.v2i2.1567

Article

Finite elemental assessment of torsional behavior of RC beams having different shear reinforcement

Warda Jannat Juhin, Raihan Uddin Ahmed, H. M. A. Mahzuz*, Md. Ariful Islam

Department of Civil and Environmental Engineering (CEE), Shahjalal University of Science and Technology (SUST), Sylhet 3114, Bangladesh
*** Corresponding author:** H. M. A. Mahzuz, mahzuz_211@yahoo.com

CITATION

Juhin WJ, Ahmed RU, Mahzuz HMA, Islam MA. Finite elemental assessment of torsional behavior of RC beams having different shear reinforcement. Building Engineering. 2024; 2(2): 1567. https://doi.org/10.59400/be.v2i2.1567

ARTICLE INFO

Received: 26 July 2024
Accepted: 13 October 2024
Available online: 25 October 2024

Abstract: In this paper, the torsional behavior of 8 beams in 4 categories with 2 different ultimate concrete compressive strengths (22.92 MPa and 43.47 MPa) was evaluated, and the best alternative of shear reinforcement pattern compared to the conventional non-welded rectangular stirrup beam (NRSB) was determined. 4 types of beams were modeled using SolidWorks, namely—Non-welded Rectangular Stirrup Beam (NRSB), Welded Rectangular Stirrup Beam (WRSB), Normal Welded Warren Truss-shaped Beam (NWWTB), and Flipped Welded Warren Truss-shaped Beam (FWWTB). The dimension and weight of reinforcement were kept the same for all beams. After simulating using ANSYS, it was seen that WRSB specimens had the largest torsional moment capacity, while NWWTB in normal orientation showed marginal improvement compared to NRSB.

Keywords: torsional behavior; concrete compressive strength; shear reinforcement pattern; non-welded rectangular stirrup beam (NRSB); welded rectangular stirrup beam (WRSB); ANSYS simulation

1. Research context and objectives

Reinforced concrete beam—a major structural element—through its lifetime faces shear stress, flexural stress, torsion, etc. Along with research on the flexural and shear capacity of reinforced concrete beams, a lot of research is also seen to be conducted on the torsional behavior as well. For example, Panchacharam and Belarbi [1] performed analysis on the torsional behavior of reinforced concrete beams strengthened with FRP composites. Deifalla and Ghobarah [2] developed an analytical model for torsional strengthening of reinforced concrete beams. Mahzuz et al. [3] conducted a study on the strength enhancement of RCC beams for different types of shear reinforcement. Three types of specimens—non-welded rectangular stirrup beam (NRSB), welded rectangular stirrup beam (WRSB), and welded Warren Truss beam (WWTB)—were prepared. All the specimens had the same concrete dimension and similar reinforcement weight. The experiment results showed that the load-carrying capacity of the WWTB was 35.28% more than the NRSB. Which exceeded WRSB, which showed a 10.16% increase in load-carrying capacity compared to NRSB.

Enhancing the beam capacity by using alternative techniques in an ongoing process of research [4,5]. Demir et al. [6] conducted a nonlinear finite element study using ABAQUS, showing a 20.8% shear capacity increase in RC T-beams with Diagonal Shear Reinforcement (DSR). Saju and Usha [7] conducted a study on the flexural strength of RC beams. From the results, it is found that 20% increase in RC beams with truss reinforcement compared to beams with normal vertical stirrups. The beams with truss reinforcement also deflected less than a normal rectangular stirrup beam. Al-Nasra and Asha [8] studied shear reinforcement types in RC beams, finding swimmer bars reduced crack width and length more effectively than traditional stirrups, with similar results for bolted and welded bars. Khan et al. [9] experimentally investigated shear reinforcement in RC beams using 45° swimmer bars. Beams with 3-legged swimmer bars showed a 9.3% higher load capacity than traditional stirrups, using 30% less shear steel. Another study discloses that WRSB specimens exhibit the maximum torsional moment (including the angle of twist) values for both mix ratios, with a range of 4.4% to 10% when compared to NRSB. However, for the WWTB specimens, the values are nearly the same, ranging from 2.4% to 1% compared to NRSB [10].

Several studies in the field of numerical simulation of RCC beams using ANSYS have been found to evaluate the capacity and strength of the beam with or without conducting an experimental test with acceptable accuracy. A work extends ANSYS modeling from smeared to a discrete approach, identifying shear cracks and simulating load-deflection curves, matching experimental results [11]. Using ANSYS, discrete modeling identified shear cracks and simulated load-deflection curves, matching experimental results. Monitoring vibration behavior and adjusting FEM parameters helped establish damage distribution in beams, with scanning laser equipment confirming modal updating's effectiveness [12]. Shear reinforcement in beams prevents premature collapse under high shear stress. Ensuring shear capacity exceeds flexural capacity helps to achieve ductile design, with failure mechanisms varying by dimensions, geometry, loading, and material properties [13]. Reinforced concrete beams face bending, transverse shear, and sometimes torsional forces. Torsion, often concurrent with bending and shear, is classified as primary or secondary. Effective torsional resistance requires closely spaced stirrups and longitudinal bars, with longitudinal bars alone improving strength by only 15% [14]. In another study, reinforced concrete beam behavior was analyzed under different shear reinforcement patterns using ANSYS software. Six 3D beams were analyzed for ultimate capacity, crack formation, and load-deflection response. All reinforcement types were similarly effective under static loading [15].

Hasan et al. [16] used ANSYS to simulate reinforced concrete beams with four shear reinforcement patterns: NRSB, WRSB, NWTB, and WWTB, analyzing flexural and shear capacities for different concrete strengths. Compared to NRSB, WWTB showed the highest load enhancement, up to 33.74%. The simulation closely matched experimental results, differing by 0.5% to 3%. Dahmani et al. [17] developed a 3D finite element model of RCC beams using ANSYS with SOLID65 elements and smeared reinforcement, validating simulation results against hand calculations. The results obtained through simulation using ANSYS were seen to be accurate as per validation. They showed the viability of using ANSYS software for analysis of RCC beams. Few researchers conducted experimental and non-linear finite element analyses of six RC beams under four-point bending using ANSYS Mechanical APDL 12.0. They compared results with IS 456:2000 code provisions, finding the code's analytical ultimate moment capacity slightly lower than experimental and FEA results [18,19]. Kandekar and Talikoti [20] studied the torsional behavior of RC beams wrapped with aramid fiber. Experimental and ANSYS simulations showed close results for ultimate loads, first cracking loads, angle of twist, and twisted beam shape. Rathi et al. [21] compared the torsional behavior of RC beams wrapped with CFRP and GFRP fabric. CFRP-wrapped beams showed greater torsional strength, angle of twist, and ductility factor than GFRP-wrapped beams.

One study numerically evaluates shear performance in reinforced concrete beams with different shear reinforcement patterns. Continuous systems (SSSSRS and DSSSRS) show 14.4% and 19.8% improved shear performance over conventional stirrups [22]. On the other hand, the nonlinear behavior of RC beams even post-tension beams is complex due to various parameters. Analysis was done by four-point bending tests on RC beams using ANSYS, considering concrete properties, mesh density, steel cushions, shear reinforcement, and convergence criteria. The findings aim to enhance ANSYS analysis guidelines for RC beams [23,24]. Another study investigates the behavior of shallow reinforced concrete beams under transverse loading using finite element analysis with ANSYS software. It focuses on stress distribution, cracks, and load-deflection relationships. Concrete is modeled with Solid65 eight-noded elements and an elastoplastic work hardening model, terminating at crushing. Reinforcement is modeled with Link180 elements, with linear elastic behavior before yield and perfectly plastic beyond that [25]. Finite Element Analysis (FEA) simulations are highly versatile, allowing for the effective modeling and analysis of even non-homogeneous numerical problems. This capability enables FEA to achieve satisfactory accuracy when compared to lab-based experiments [26–29].

Despite extensive research on the torsional behavior and shear reinforcement of reinforced concrete (RC) beams, there remains a significant gap in comprehensive studies using advanced numerical simulations to analyze different shear reinforcement patterns under torsional loads. Though there are few studies as mentioned above, a detailed numerical investigation using ANSYS on the torsional behavior of RC beams with different shear reinforcement patterns has not been thoroughly explored. This study aims to fill this gap by conducting a nonlinear finite element analysis (FEA) using ANSYS to compare the torsional performance of RC beams with various shear reinforcement configurations. By doing so, it seeks to provide deeper insights into optimizing shear reinforcement for enhanced torsional resistance, potentially reducing the need for extensive experimental testing and offering more efficient design solutions for structural engineers.

Based on the above contextual foundation, the knowledge gap is clearly identified. Therefore, the objective of this research is:

- To analyze the torsional behavior of reinforced concrete beams with four different types of shear reinforcement patterns (NRSB, WRSB, NWWTB, FWWTB) using ANSYS.
- To identify the most effective shear reinforcement pattern in enhancing torsional resistance compared to the conventional non-welded rectangular stirrup beam (NRSB).

2. Research method

2.1. Selection of models

In total, eight beams were modeled, and their torsional behavior was analyzed. These eight beams were divided into three patterns with two different concrete compressive strengths. All the beams were of the same dimension, i.e., length = 1220 mm, width = 127 mm, and height = 203 mm. The concrete cover for reinforcement was 30.5 mm on the sides and 43.5 mm on the top and bottom faces, meeting the minimum requirements. The reinforcement patterns of NRSB, WRSB, NWWTB, and FWWTB are shown in **Figures 1–4**. All the flexural reinforcements were 16 mm dia rebar, and all the shear reinforcements were 100 mm dia bars. To observe the effect of torsion, the weight of steel in all patterns is kept the same. Thus, the costs of the different patterns of the beam were the same. This could make the comparison easier. The flow diagram of the study is shown in **Figure 5**.

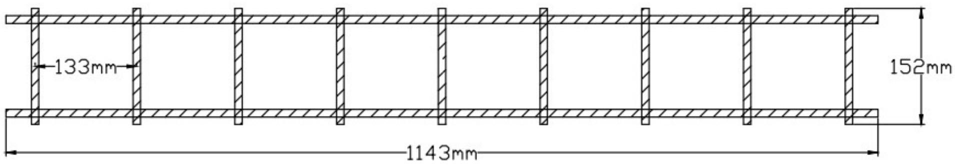


Figure 1. NRSB reinforcement pattern and dimension.

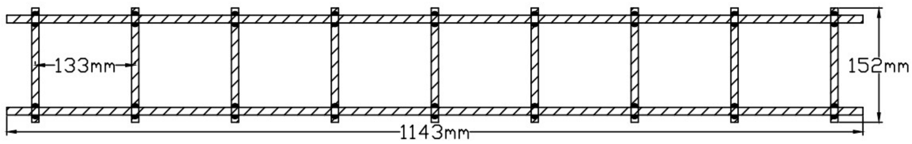


Figure 2. WRSB reinforcement pattern and dimension.

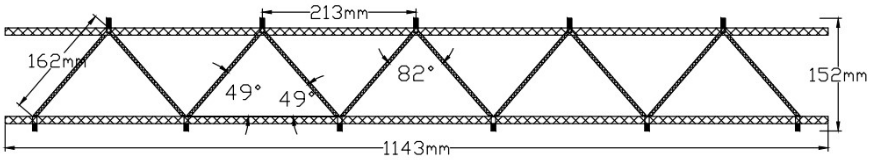


Figure 3. NWWTB reinforcement pattern and dimension.

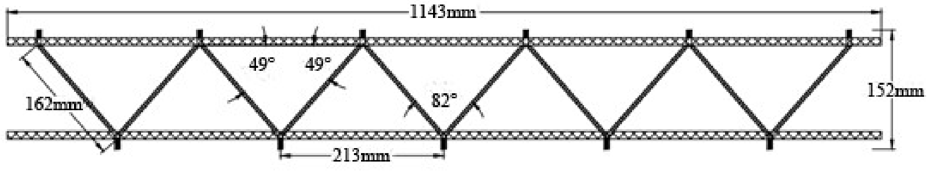


Figure 4. FWWTB reinforcement pattern and dimension.

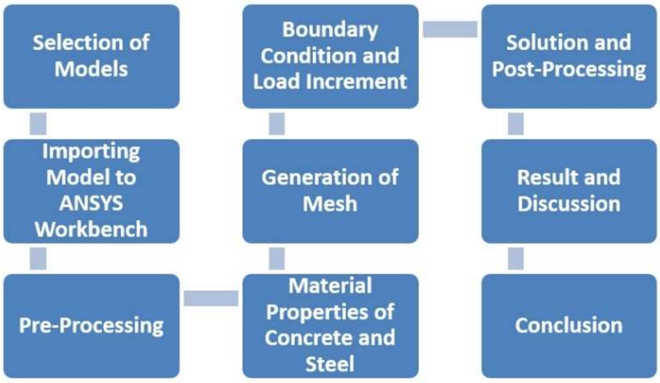


Figure 5. Flow diagram of research method.

The concrete model and the different reinforcement models are shown in **Figures 6–9**. Note that the truss models were created using SolidWorks and later exported to ANSYS Workbench.

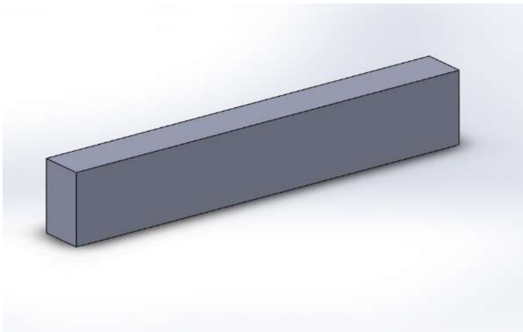


Figure 6. Created concrete model in solid works.

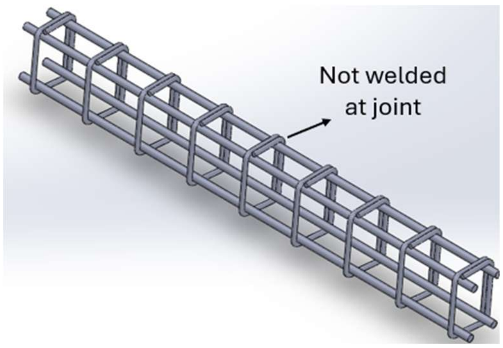


Figure 7. NRSB reinforcement model.

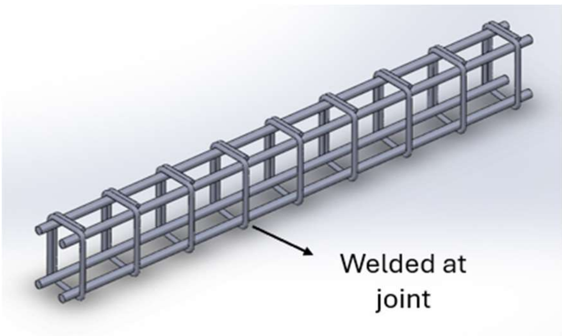


Figure 8. WRSB reinforcement model.

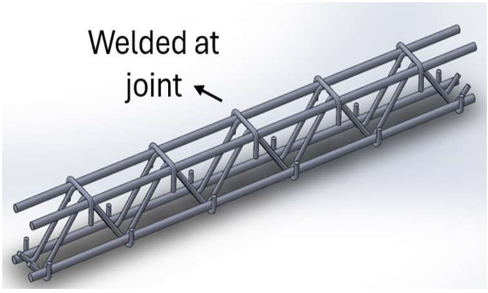


Figure 9. WWTB reinforcement model.

2.2. Importing model to ANSYS workbench

SolidWorks uses a proprietary file extension for image files called SLDPRT, which stands for SolidWorks Part file. ANSYS does not directly support the file format. So, in order to import the file to the ANSYS Workbench, the SLDPRT file needed to be transformed into a vendor-neutral file format that ANSYS supports, such as Parasolid, IGES, STEP, etc. The SLDPRT files were converted to IGES file format directly by using SolidWorks and then imported to ANSYS. The Initial Graphics Exchange Specification (IGES) is a vendor-neutral file format that allows the digital exchange of information among computer-aided design systems.

2.3. Pre-processing

The preprocessing process contains assigning the material properties of different parts, meshing, applying constraints, and applying loads. The preprocessing method will be discussed in brief within the next few chapters.

There are several methods to evaluate the non-linear behavior of concrete. In this paper, the modified Hognestad piecewise elastic model [30] was used to obtain the compressive uniaxial stress-strain relationship. The following Equations (1)–(4) were used to compute the engineering multilinear isotropic stress-strain curve for the concrete.

$$E_c = 4730\sqrt{f_c'} \quad (1)$$

$$f = \frac{E_c\,\varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2} \quad (2)$$

$$\varepsilon_0 = \frac{2f_c'}{E_c} \quad (3)$$

$$E_c = \frac{f}{\varepsilon} \quad (4)$$

2.4. Material properties of concrete and steel

Elastic Perfectly Plastic Material Model was used for modeling the steel reinforcement materials. The grade of steel used in the beams was 500 W, i.e., the yield strength of steel is 500 MPa. The values of Young's modulus, tangent modulus, and Poisson's ratio were taken as 200,000 MPa, 1450 MPa, and 0.3, respectively. Two concrete compressive strengths are considered for the study; one is relatively low (22.92 MPa), and another is moderate (43.47 MPa) 28-day strengths. The stress-strain curve of steel and two different concrete compressive strengths are shown in **Figures**

10 and **11**. Mild steel electrodes were used, and the electrodes were E6012. The tensile strength of the electrode was 414 MPa. Bilinear isotropic hardening data were inserted, and material was assigned.

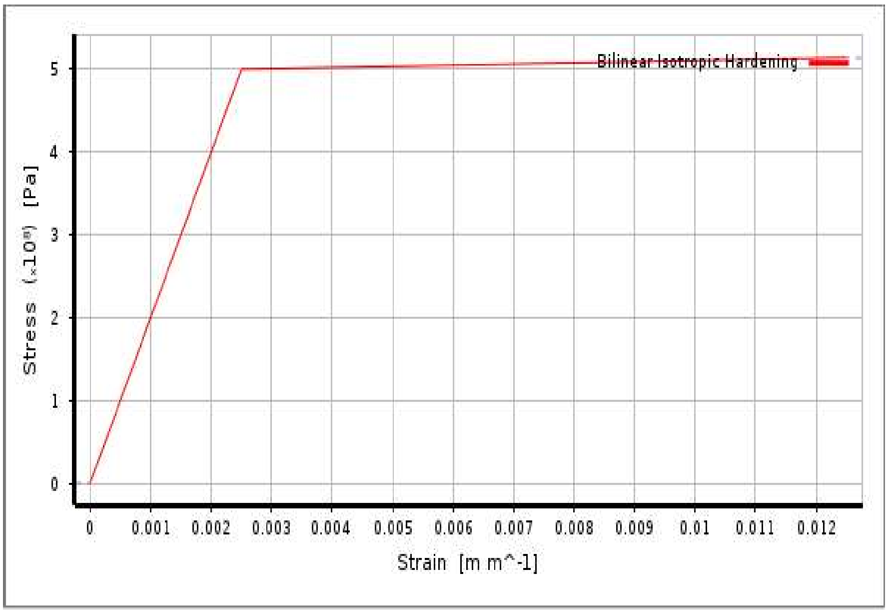


Figure 10. Stress-strain curve for steel reinforcement.

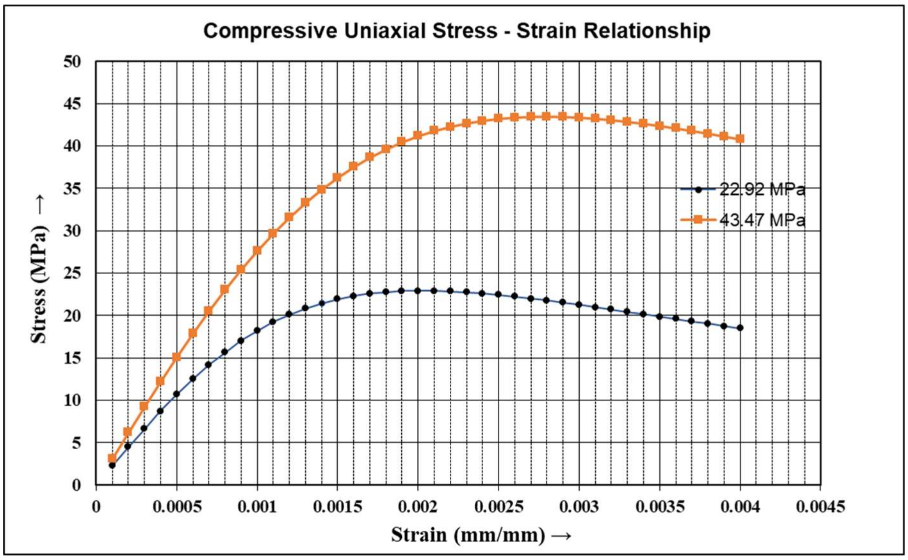


Figure 11. Uniaxial stress-strain curve for two different concrete compressive strengths (Poisson's ratio-0.18).

2.5. Generation of mesh

Meshing is an integral part of the computer-aided simulation process. The mesh affects the accuracy, convergence, and speed of the solution. Furthermore, the time it takes to create and mesh a model is often a significant part of the time it takes to get results from a CAE solution. The better and more automated the meshing tools, the better the solution. For solid models, ANSYS meshing technologies provide robust, well-shaped, quadratic tetrahedral meshing on even the most complex geometries. As the model is comprised of rectangular solids and cylindrical solids, the quadratic tetrahedral mesh was created in the patch confirming method. The mesh element size was 8 mm according to mesh sensitivity analysis. The number of elements varied from 66,411 to 66,832, and the number of nodes varied from 32,565 to 32,590 depending on the model. The meshed parts are shown in the following figures (**Figures 12–16**).

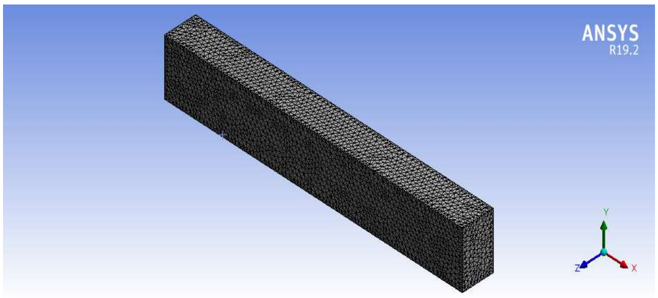


Figure 12. Concrete model after meshing.

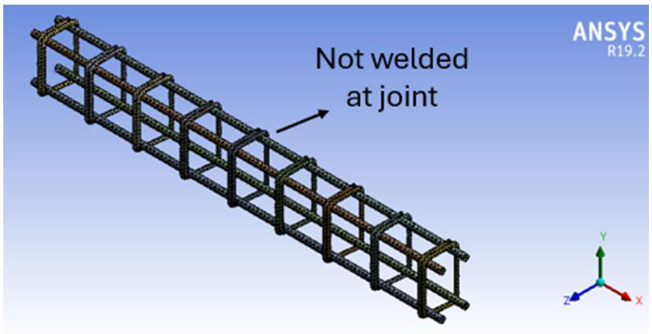


Figure 13. Meshed model of NRSB reinforcement.

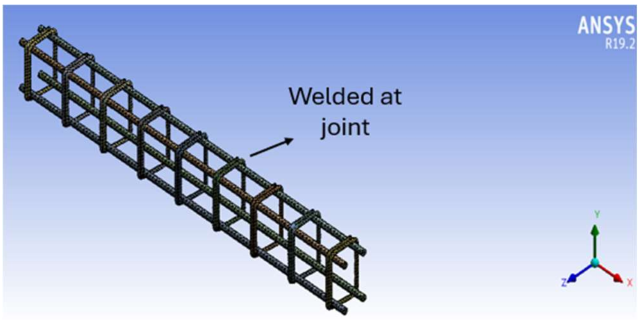


Figure 14. Meshed model of WRSB reinforcement.

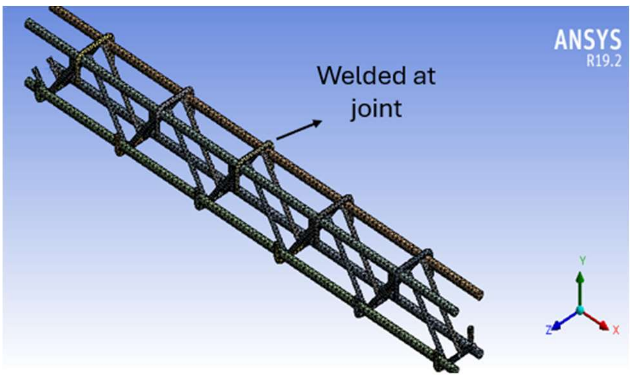


Figure 15. Meshed Model for WWTB Reinforcement (Normal orientation).

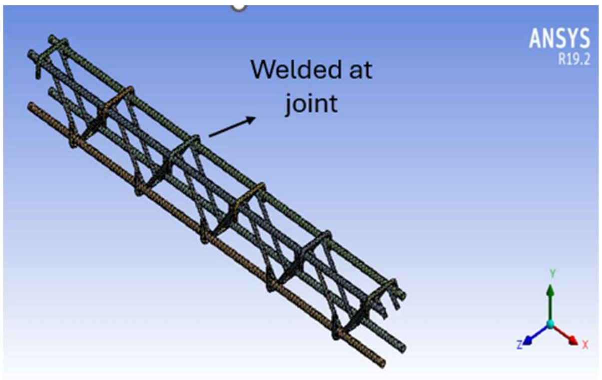


Figure 16. Meshed model for WWTB reinforcement (Flipped orientation).

2.6. Boundary condition and load increment

The beam had fixed support at one end. Typically, plastic hinges in terms of boundary conditions are between 0.1 and 0.2 for a cantilever beam; consideration of 0.2 is more common. Fixed support was selected directly from the ANSYS Workbench command list (**Figure 17**). The total moment applied to the finite-element model is divided into a series of increments called steps. A step corresponds to a set of loads for which you want to obtain a solution and review results. Solving an analysis with nonlinearities requires convergence of an iterative solution procedure. The convergence of this solution procedure requires the load to be applied gradually with solutions carried out at intermediate load values. These intermediate solution points within a step are referred to as sub-steps. Essentially, a sub-step is an increment of load within a step at which a solution is carried out. The moment is applied on the free end as shown in **Figure 18**, and the number of steps and sub-steps is shown in **Figure 19**.

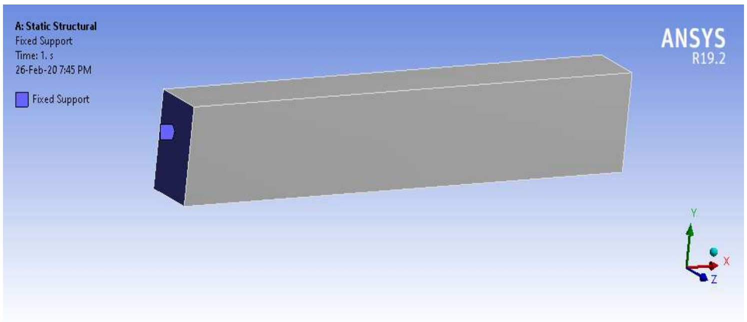


Figure 17. Assigned fixed support.

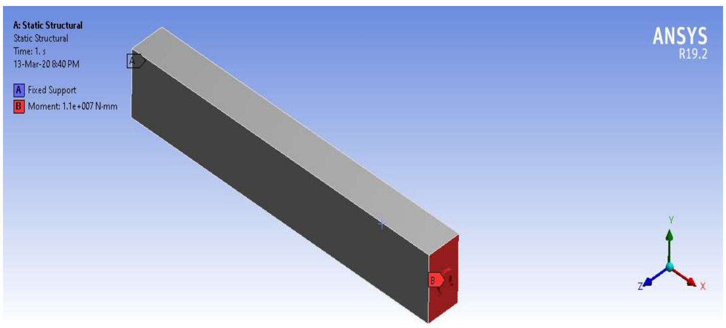


Figure 18. Assigned moment.

Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	On
Define By	Substeps
Initial Substeps	50.
Minimum Substeps	50.
Maximum Substeps	250.

Figure 19. Number of steps and sub-steps.

2.7. Solution and post-processing

The meshed models were analyzed. After the analysis, required data or images are extracted from ANSYS for further analysis. For further analysis, the essential data are loading values, stress distribution, and maximum equivalent stress in both concrete and steel. In addition, all the values were imported from ANSYS to Excel for making the necessary graphs. Moreover, the required screenshots were taken from ANSYS. Thereafter, all the graphs and analysis are presented in the 'Result and Discussion' section.

3. Result and discussion

In an under-reinforced beam, steel yields while concrete remains under-stressed. Cracks appear on the beam as the stress in the steel reaches the yield point. The torsional moment capacity of the beams until the steel yields is presented in **Figures 20** and **21** for fc' of 22.92 MPa and 43.47 MPa, respectively. The ultimate torsional moment of each beam is presented in **Table 1**. Note that the FWWTB-type beam was out of experimental data. The other beams show a little variation in results ranging from 3.25%–6.95%. Also, the information related to the ultimate angle of twist is shown in the table. The ultimate torsional moment of each type of beam was taken and compared with NRSB. The comparison is shown in **Figures 22** and **23** for 22.92 MPa and 43.47 MPa, respectively. From **Figures 22** and **23**, it can be said that the torsional moments of +0.5%, −10.1%, and +12.1% are seen for NWWTB, FWWTB, and WRSB with respect to NRSB for the concrete compressive strength of 22.92 MPa. The respective values are +1.9%, −1.8%, and +6.5% for the concrete compressive strength of 43.72 MPa. Therefore, it can be seen that the WRSB beam has the highest ultimate torsional moment carrying capacity and the ultimate angle of twist, while FWWTB has the lowest in both.

The stress distribution across concrete for NRSB, WRSB, NWWTB, and FWWTB is shown in **Figures 24–27**, respectively. By the visual comparison of **Figures 20** and **21**, it is seen that more stress and moments can be shared by the reinforcement of WRSB compared to others. Also, from **Figures 24–27**, it can be seen that the contribution of reinforcement is more obvious in WRSB and NRSB. FWWTB and NWWTB are showing more red sections than others, having less contribution of reinforcement.

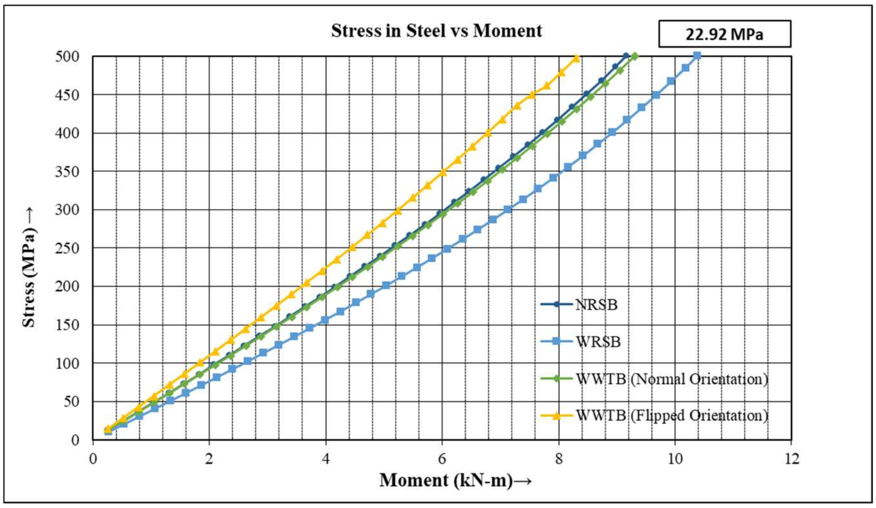


Figure 20. Stress vs applied moment for *fc′* of 22.92 MPa.

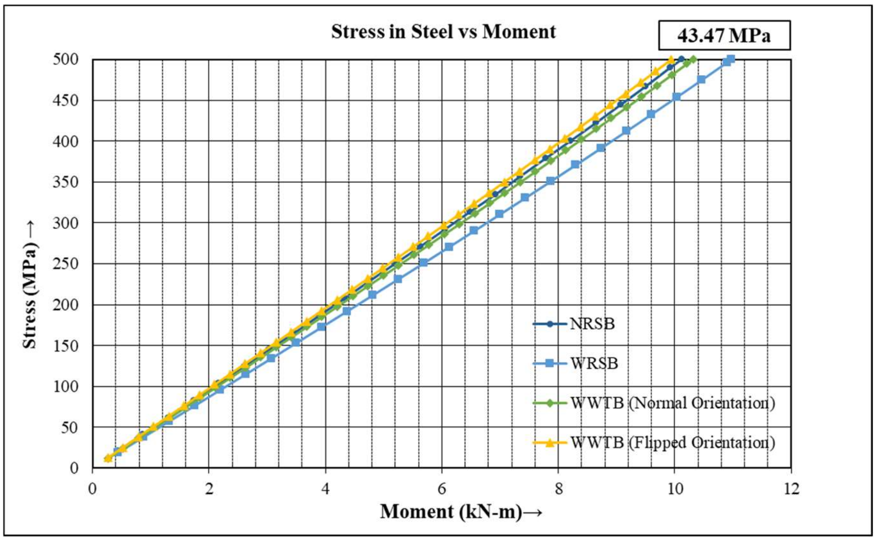


Figure 21. Stress vs applied moment for *fc′* of 43.47 MPa.

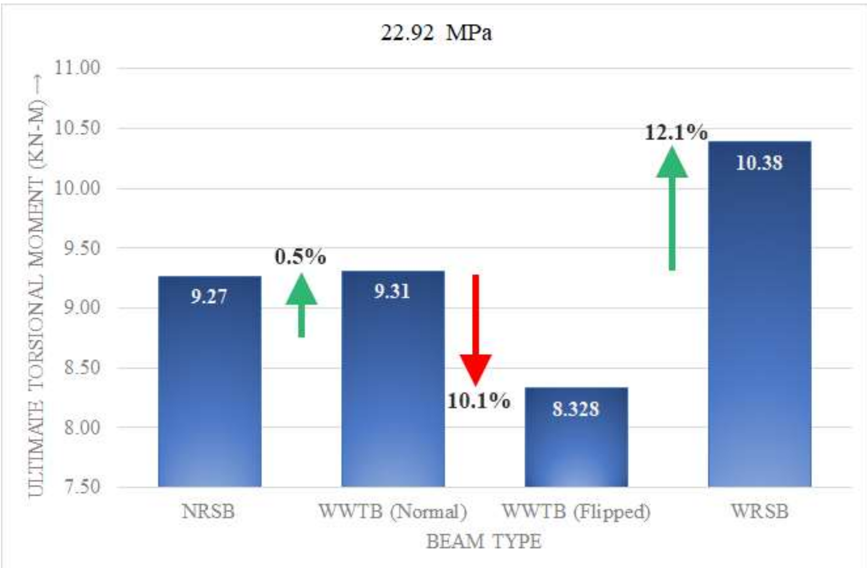


Figure 22. Increment compared to NRSB for *fc′* of 22.92 MPa.

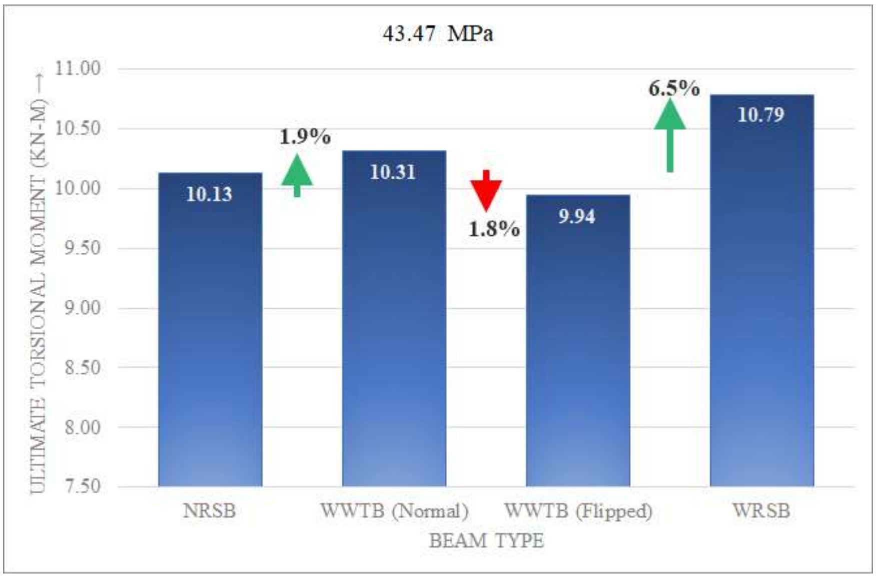


Figure 23. Increment compared to NRSB for *fc'* of 43.47 MPa.

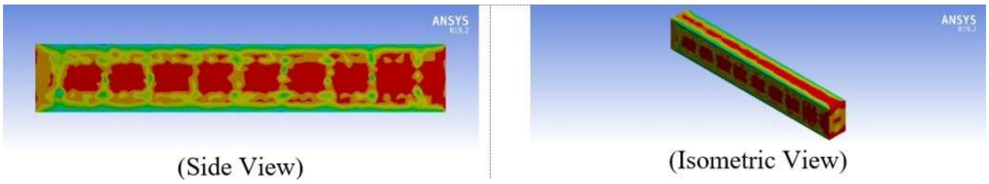


Figure 24. Stress distribution across NRSB.

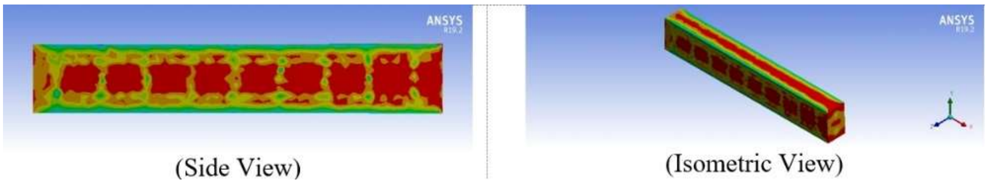


Figure 25. Stress distribution across WRSB.

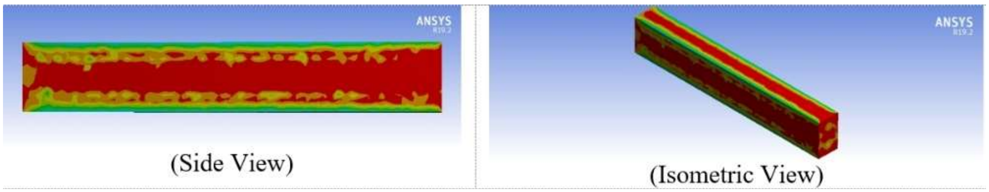


Figure 26. Stress distribution across NWWTB.

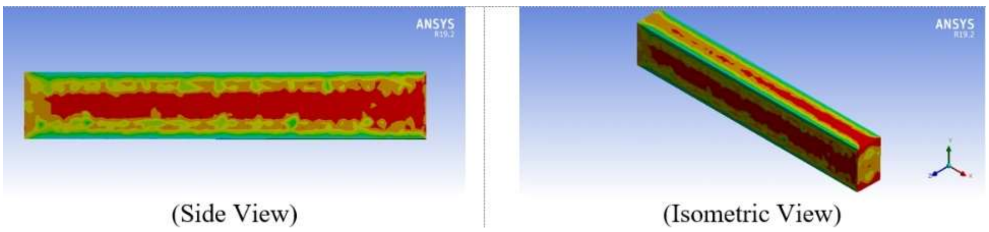


Figure 27. Stress distribution across FWWTB.

Table 1. Ultimate torsional moment and angle of twist for each *fc'*.

28-day compressive strength of Concrete, *fc'*	Beam Type	FEA Ultimate Torsional Moment	FEA Ultimate Angle of twist, Ø (Rad/m) × 10^{-3}
22.92 MPa	NRSB	9.26	13.00
	WRSB	10.38	14.73
	NWWTB	9.31	13.20
	FWWTB	8.33	11.81
43.72 MPa	NRSB	10.13	10.43
	WRSB	10.78	11.11
	NWWTB	10.31	10.62
	FWWTB	9.94	10.40

4. Conclusion

For reinforced concrete beams, torsional failure is a brittle type failure. The pattern of shear reinforcement plays an important role in preventing this problem. In this research, FE analysis (supported by ANSYS and SOLIDWORKS) is done for varying patterns of shear reinforcement (i.e., Welded Rectangular Stirrup Beam (WRSB), Normal Welded Warren Truss-shaped Beam (NWWTB), and Flipped Welded Warren Truss-shaped Beam (FWWTB), keeping the performance of the conventional one in parallel (i.e., Non-Welded Rectangular Stirrup Beam (NRSB)). In conclusion, the following comments can be presented:

a) For both values of compressive strength, WRSB had the highest ultimate torsional moment and angle of twist capacity.

b) After WRSB, NWWTB, followed by NRSB, showed better performance. FWWTB showed the lowest capacity.

c) For WRSB, torsional moment was 12.1% and 6.5% higher than NRSB for concrete compressive strength of 22.92 MPa and 43.47 MPa, respectively, whereas the torsional moment for NWWTB was 0.5% and 1.9% higher than NRSB for the two values, and FWWTB performed worse than NRSB by 10.1% and 1.8% higher than NRSB for concrete compressive strength of 22.92 MPa and 43.47 MPa, respectively.

d) Experimental investigation ensuring the mentioned physical condition (in Section 3.0 Research Method) can give a better understanding. More analysis can be done using ANSYS Mechanical APDL, particularly using the CPT 215 element, in order to get the cracking pattern and angle of twist from ANSYS Mechanical APDL.

e) The result got from this study may be useful for further study in this field as well as for practicing professionals.

f) The data presented in this paper is entirely generated through software operations, with no validation against experimental data. As a result, there is an opportunity to strengthen the findings through experimental investigation. This limitation should be acknowledged as a potential shortcoming of the current study.

Author contributions: Conceptualization, WJJ, RUA and HMAM; methodology, HMAM, WJJ and RUA; software, WJJ and RUA; validation, WJJ and RUA; formal analysis, RUA; investigation, RUA; resources, MAI; data curation, WJJ and RUA; writing—original draft preparation, WJJ, RUA and HMAM; writing—review and editing, HMAM and MAI; visualization, HMAM and MAI; supervision, HMAM; project administration, HMAM; funding acquisition, WJJ and RUA. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

Abbreviations

E_c	Modulus of elasticity of concrete
f	Stress at any strain, ε, MPa
ε	Strain at stress, f
ε_0	Strain at ultimate compressive strength, f_c'
NRSB	Non-welded Rectangular Stirrup Beam
WRSB	Welded Rectangular Stirrup Beam
NWWTB	Normal Welded Warren Truss-shaped Beam and
FWWTB	Flipped Welded Warren Truss-shaped Beam

References

1. Panchacharam S, Belarbi A. Torsional behavior of reinforced concrete beams strengthened with FRP composites. First FIB Congress, Osaka, Japan. 2002; 1: 01-110.
2. Deifalla A, Ghobarah A. Full torsional behavior of RC beams wrapped with FRP: Analytical model. Journal of Composites for Construction. 2010; 14(3): 289-300.
3. Mahzuz HMA, Ahmed M, Islam MdM, et al. Influence of truss-type and welded reinforcement in concrete beam. International Journal of Structural Engineering. 2022; 12(2): 144. doi: 10.1504/ijstructe.2022.121911
4. Prasanthni P, Priya B, Palanisamy T, et al. Enhancing PVCC beam performance through PVA fiber and basalt fabric in sustainable construction: ductility, strength, and energy absorption improvements. Matéria (Rio de Janeiro). 2024; 29(1). doi: 10.1590/1517-7076-rmat-2023-0299
5. Mohanraj R, Senthilkumar S, Padmapoorani P. Mechanical properties of RC beams with AFRP sheets under a sustained load. Materiali in Tehnologije. 2022; 56(4). doi: 10.17222/mit.2022.481
6. Demir A, Caglar N, Ozturk H, et al. Nonlinear finite element study on the improvement of shear capacity in reinforced concrete T-Section beams by an alternative diagonal shear reinforcement. Engineering Structures. 2016; 120: 158-165. doi: 10.1016/j.engstruct.2016.04.029
7. Saju SM, Usha S. Study on flexural strength of truss reinforced concrete beams. International Research Journal of Engineering and Technology. 2016: 1541-1545.
8. Al-Nasra MM, Asha NM. Shear reinforcements in the reinforced concrete beams. American Journal of Engineering Research (AJER). 2013; 2(10): 191-199.
9. Khan MU, Fahad M, Shahzada K. Shear Capacity Assessment of Reinforced Concrete Beams Using Swimmer Bars as Shear Reinforcement. International Journal of Civil Engineering. 2020; 2(6): 14-20. doi: 10.14445/23488352/ijce-v2i6p104
10. Mahzuz HMA, Nury AH, Ahmed M, et al. Enhancing torsional performance of reinforced concrete beams: a comparative analysis of shear reinforcement strategies. Discover Civil Engineering. 2024; 1(1). doi: 10.1007/s44290-024-00029-3
11. Khan HU. Identification of shear cracks in reinforced beams using finite element method (ANSYS). Pakistan Journal of Science. 2014: 66(1).
12. Subramani T, Manivannan R, Kavitha M. Crack identification in reinforced concrete beams using ANSYS software. J. Eng. Res. Appl. 2014; 4(6): 133-141.
13. Cucchiara C, La Mendola L, Papia M. Effectiveness of stirrups and steel fibres as shear reinforcement. Cement and Concrete

Composites. 2004; 26(7): 777-786. doi: 10.1016/j.cemconcomp.2003.07.001
14. Nilson AH, Dolan CW, Darwin D. Design of concrete structures, 14th ed. McGraw-Hill Education; 2009.
15. Saifullah I, Hossain MA, Uddin SMK, et al. Nonlinear analysis of RC beam for different shear reinforcement patterns by finite element analysis. International Journal of Civil & Environmental Engineering. 2011; 11(1): 63-74.
16. Hasan K, Alam MM, Mahzuz HMA, Hasan K. FE simulation of reinforced concrete beam using ANSYS for several patterns of shear reinforcement. In: Proceedings of the 5th International Conference on Advances in Civil Engineering, CUET, Chattogram-4349; 2021; Bangladesh. pp.143-150.
17. Dahmani L, Khennane A, Kaci S. Crack identification in reinforced concrete beams using ANSYS software. Strength of Materials. 2010; 42(2): 232-240. doi: 10.1007/s11223-010-9212-6
18. Vasudevan G, Kothandaraman S, Azhagarsamy S. Study on Non-Linear Flexural Behavior of Reinforced Concrete Beams Using ANSYS by Discrete Reinforcement Modeling. Strength of Materials. 2013; 45(2): 231-241. doi: 10.1007/s11223-013-9452-3
19. Vasudevan G, Kothandaraman S. Behavior prediction of RC beams-comparison of experimental, FEA and analytical methods. In: IEEE-International Conference on Advances in Engineering, Science and Management (ICAESM-2012). pp. 365-370
20. Kandekar SB, Talikoti RS. Study of torsional behavior of reinforced concrete beams strengthened with aramid fiber strips. International Journal of Advanced Structural Engineering. 2018; 10(4): 465-474. doi: 10.1007/s40091-018-0208-y
21. Rathi S, Kandekar S, Talikoti R. Strengthening of RC beam using carbon and aramid fiber for its torsional behavior. Int J Sci Res Dev. 2015; 3(07): 416-419.
22. Azimi M, Ponraj M, Bagherpourhamedani A, et al. Shear capacity evaluation of reinforced concrete beams: finite element simulation. Jurnal Teknologi. 2015; 77(16). doi: 10.11113/jt.v77.6400
23. Vasudevan G, Kothandaraman S. Parametric study on Nonlinear Finite Element Analysis on flexural behaviour of RC beams using ANSYS. International journal of civil & structural engineering. 2011; 2(1): 98-111.
24. Fanning P. Nonlinear Models of Reinforced and Post-tensioned Concrete Beams. Electronic Journal of Structural Engineering. 2001; 1(2): 111-119. doi: 10.56748/ejse.1182
25. Musmar MA, Rjoub MI, Hadi MA. Nonlinear finite element analysis of shallow reinforced concrete beams using SOLID65 element. Elastic. 2006; 25743: 0-3.
26. Mohanraj R, Vidhya K. Evaluation of compressive strength of Euphorbia tortilis cactus infused M25 concrete by using ABAQUS under static load. Materials Letters. 2024; 356: 135600. doi: 10.1016/j.matlet.2023.135600
27. Krishnasamy R, Johnson SC, Kumar PS, et al. Experimental Investigation of Lateral Load Test on Diagonal Braced 3M Glass Fiber Reinforced Polymer Transmission Tower. Power Research. A Journal of CPRI. 2024: 225-231. doi: 10.33686/pwj.v19i2.1150
28. Ravikumar K, Palanichamy S, Singaram CJ, Rajendran M. Crushing performance of pultruded GFRP angle section with various connections and joints on lattice towers. Matéria (Rio de Janeiro). 2023; 28(1): e20230003
29. Ravikumar K, Singaram CJ, Palanichamy S, et al. Testing and Evaluation of Buckling and Tensile Performance of Glass Fiber–Reinforced Polymer Angle Section with Different Joints/Connections. Journal of Testing and Evaluation. 2024; 52(1): 621-638. doi: 10.1520/jte20230010
30. MacGregor JG, Wight JK, Teng S, Irawan P. Reinforced concrete: Mechanics and design. Prentice Hall Upper Saddle River, NJ; 1997. p. 3.

Building Engineering 2024, 2(2), 1510.
https://doi.org/10.59400/be.v2i2.1510

Article

Fulfilling the potentials of residential solar energy in Egypt

Atef Badr

Department of Civil Engineering and Quantity Surveying, The Military Technological College, Muscat, P.C. 111, Oman; atef.badr@mtc.edu.om

CITATION

Badr A. Fulfilling the potentials of residential solar energy in Egypt. Building Engineering. 2024; 2(2): 1510.
https://doi.org/10.59400/be.v2i2.1510

ARTICLE INFO

Received: 5 July 2024
Accepted: 19 September 2024
Available online: 4 October 2024

Abstract: Energy plays a very important role in Egypt's economic development, but the country has a gap between its produced energy and the demand of its growing population. Utilization of solar power systems in Egypt could help the country to close this gap and fulfil its national and international obligations. However, since 1980, the focus in Egypt has been on large-scale industrial solar projects. Limited attention is given to smaller systems for typical residential buildings. The aim of this research, therefore, is to highlight the potential of small residential solar systems (SRSS) in Egypt. With the huge number of residential buildings accommodating more than 115 million Egyptians, SRSS could be the unearthed gem of a sustainable source of energy in Egypt. The geographical location of Egypt and climate were used to generate solar data using the Global Solar Atlas application. The amounts of monthly and annual solar irradiations were calculated and analysed to decide the best orientation of the system (facing east, west, north, and south), identify the optimum tilt angle of the system, and determine the size of the solar panels. A case study was used to illustrate the procedures of designing SRSS for a typical residential building in Egypt. The results showed that a 26 kWp SRSS oriented facing the east with an optimum tilt angle between 15° and 30° could produce an annual total output of electricity more than the annual demand of the occupants of the studied residential building. Such a system would fit easily on the roof of the building. It was concluded that the installation of SRSS in Egypt could help the country meet the demand of its ever-increasing population if properly regulated, financed, and managed. It is recommended that Egypt develop and implement policies to make installations of SRSS an attractive choice among homeowners and investors by introducing encouraging incentives and creating a competitive market with affordable SRSS.

Keywords: sustainability; solar power; energy efficiency; residential buildings

1. Introduction

Energy used in everyday human activities is huge, and its environmental impact is substantial. In the last three decades, researchers have paid great attention to the impact of different human activities and processes on the environment. Thus, concepts such as sustainable development, greener human activities, green processes, green technologies, and protection of natural resources have emerged. However, the global demand for energy is increasing due to the continuous growth of the world's population, which could approach ten billion by 2050. Moreover, it is projected that the population in cities and urban areas will be more than two-thirds of the world population in the next two decades, leading to further demand for infrastructure for service [1–2].

In 2021, Tadros et al. [3] reported that developing countries in Asia and Africa will witness the fastest growth in urbanization, with seven of the ten countries with the fastest projected urbanization rates between 2018 and 2050 being in Africa. Energy plays a very important role in the economic development of developing countries, but many of them have gaps between their produced energy and the demand of their growing populations. One of those countries is Egypt.

Egypt is the third-most populous country in Africa, after Nigeria and Ethiopia. With a current population of about 115 million, it is the 14th most populous country in the world. **Figure 1** presents the growth of its population in the past, present, and future prediction by the UN Population Division.

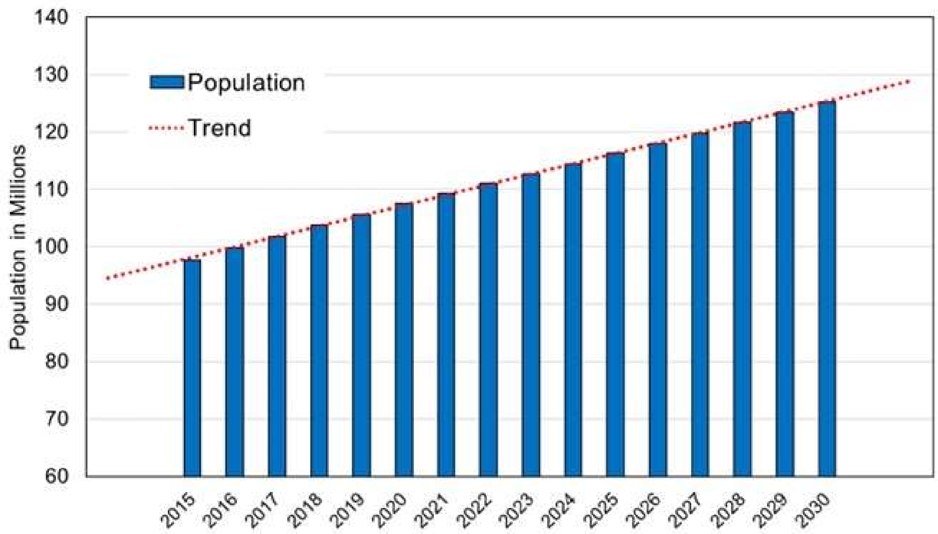


Figure 1. Projection of Egypt population, 2015 to 2030 (UN Population Division).

The total population in Egypt is predicted to continuously increase between 2024 and 2030 by more than 10%, from 115 to 125 million [4]. The trend indicates ten consecutive years of population growth, with no sign of fading. In response to this ever-increasing population, Egypt is witnessing a rapid rate of construction to accommodate its expanding population and the demand for affordable housing with basic infrastructure services. Construction of buildings requires enormous resources, including materials and energy, among other resources that are vital for the proper operation of any building. In addition, Egypt is one of those developing countries progressing in their development and trying to achieve its ambitions of becoming a recognised industrial state. Therefore, energy plays a very important role in Egypt's economic development. However, the country has limited energy resources, with the current per capita installed power being less than 0.50 MW/c, as shown in **Table 1** [5]. According to the IEA [6], Egypt will need some 19 GW of new capacity by 2030 to meet the forecast electricity demand. Attempting to increase the production of energy by traditional sources is a real challenge. Several international organisations suggested that Egypt should aim to exploit renewable energy (RE) sources [6,7].

Recently, Egypt recognized that sustainable development requires sustainable resources and deemed the current energy situation not sustainable. The Egyptian Supreme Council for Energy adopted an ambitious plan aiming to generate 20% of Egypt's electricity needs from RE resources by 2027 [8,9]. However, the focus is on large-scale industrial projects, such as concentrated solar power (CSP), which are employed in Egypt for industrial productions of electricity [10]. Other large industrial solar systems include generation of electricity from ground-mounted large-scale systems, which include photovoltaic panels—also known as modules or solar collectors—mounted on fixed or movable tilted structures aligned in a matrix of rows and columns. Unfortunately, the utilization of solar systems in residential buildings is very limited and only exists in the form of solar collectors used for individual domestic water heaters. Furthermore, most of these water heater units have been installed in state-owned new developments in new cities and some hotels in remote tourist resorts.

Table 1. Egypt's installed electric power indicators (2012–2032), adapted from Comsan et al. [5].

Year	2012	2017	2022	2027	2032
Population (million)	91.2	101.8	110.9	119.8	128.7
Per capita installed power (MW/c)	0.32	0.37	0.43	0.48	0.54
Total (GW)	29.0	37.8	47.1	57.7	70.0
Installed power annual growth rate (%)	6.5	6.1	4.9	4.5	4.3

This research, therefore, aims to highlight the huge potential for solar energy applications in residential buildings. With the huge number of residential buildings accommodating more than a hundred million Egyptians, small residential solar systems (SRSS) could provide an invaluable source of clean energy in Egypt. The implementation of SRSS could trigger the development of cost-effective alternative renewable energy in Egypt, which could help in closing the gap between the huge demand and its limited energy from conventional resources.

This paper is structured to report the outcome of this research. Section 2 provides a background on solar energy and the three generations of photovoltaic (PV) technology. Section 3 discusses the current energy resources in Egypt, including solar energy, and highlights the need for implementing more RE to supplement the limited conventional resources. Then, the small residential solar system (SRSS) is introduced in Section 4, showing the possibilities of interconnecting the system to the power grid. Section 5 includes discussion on quantifying the potentials of SRSS in Egypt and then uses a case study to illustrate the initial design of a SRSS. The main taking-away outcomes are then concluded in Section 6, which is followed by some recommendations in Section 7. Finally, the limitations of this research and suggested further work are given in Section 8.

2. Solar power systems

Producing the energy needed for any activity or process from a sustainable renewable source could reduce its negative impact on the environment. RE produced onsite could be converted to electricity before using in any application. Alternatively, it could be integrated directly into the process or operation. Integrating renewable energy within any process could enhance its own sustainability credentials. For example, Badr [11] suggested that the environmental benefits of integrating renewable energy in desalination could enhance its sustainability and reduce its impact on the environment, such as a photovoltaic (PV)-powered desalination unit [12,13]. Several sources of renewable energy could be utilised including wind, biomass, and geothermal, but solar power is the most obvious candidate. Solar energy can be utilised for sustained energy supply. It could help in reducing the impact on the environment [14,15].

Photovoltaic (PV) is a promising process that can convert solar irradiation to electricity [16]. Integrating PV systems within new building structures, known as Building Integrated Photovoltaics (BIPV), requires installing fully functional PV modules within the building enclosure, preferably during the construction process. Compared to non-integrated systems, BIPV offers advantages such as reducing utilised land. It could also be used as a valuable marketing feature for planned developments [17–20]. However, most of the PV systems installed worldwide are from first-generation PV technologies. Li et al. [21] provided an insight into the development of PV technology from the first generation to the current third generation. The latter focuses more on utilizing new materials in developing more efficient PV panels with lightweight structure and reduced material consumption [22]. There is evidence in the literature that the progress in the development of such systems is promising and that the new generation of PV systems is more efficient, economical, and has a better environmental impact. For example, Li et al. [17] investigated the economic and environmental performance of new types of BIPV in three countries in Europe and proved that they are economically feasible systems. They concluded that the outcome of their study can serve as valuable guidelines for the design of BIPV projects. In all cases, and regardless of the PV technology generation, all PV systems require exposure to significant sun irradiation, which in turn depends on the geographical location and optimum orientation of the system.

3. Energy resources and solar power in Egypt

Figure 2 shows the share of different primary energy sources in the production of electricity in Egypt. The figure illustrates the change of the pattern over the years in the past, present, and projected in the future until 2050 [6].

The share of different primary energy sources in electricity generation changes with time. In 2008, gas was the main source, representing about 85% of the total electricity production. This was followed by 12.5% for hydropower and 1.5% for wind power [23].

The DLR (German Aerospace Center) forecasted the electricity consumption for Egypt up until 2050, considering the expected population increase and the expected economic growth. DLR indicated that meeting the demand would not be possible by relying on conventional energy sources and suggested that the country should aim to exploit renewable energy sources. It also suggested that solar energy should be among the prime sources of renewable energy and that Egypt shall target a share of more than 50% by the year 2050 [7].

Renewable energy (RE) resources in Egypt include wind, solar, and biomass. Since the 1970s and 1980s, Egypt has dedicated effort to exploit RE potentials. A renewable energy strategy was formulated and included in the national energy planning. In 1986, the New and Renewable Energy Authority (NREA) was established to progress efforts to develop and introduce RE technologies in Egypt.

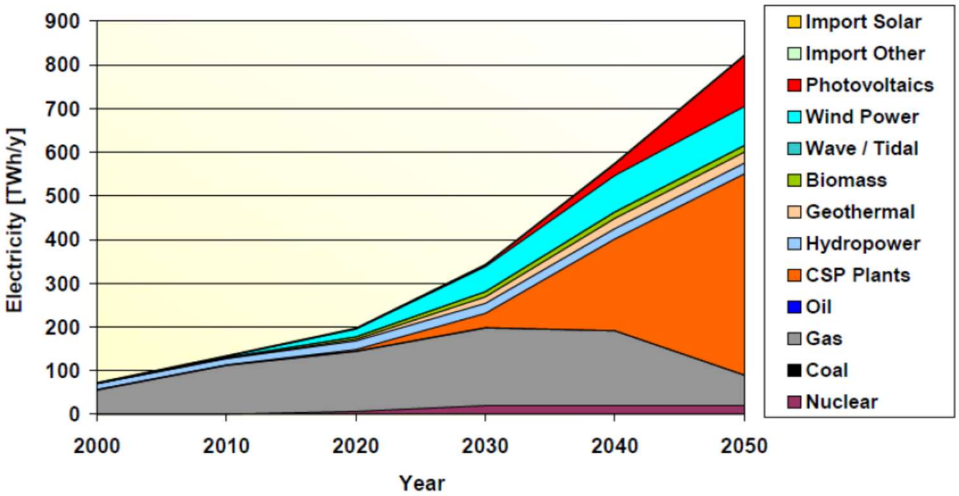


Figure 2. Electricity production by primary energy sources in Egypt [6].

Egypt's strategic plan, aiming to generate one-fifth of the country's electricity needs from RE resources by 2027, was announced by the Egyptian SCoE in 2007 [5,9]. To achieve this target, the Ministry of Electricity and Energy (MoEE) updated its electricity generation plans, as shown in **Table 2**. The share of electricity generation from RE sources was significant but focused more on wind energy up to 2027. The plan opened the door for private sector involvement in the process and encouraged investors to participate and invest in developing the country's RE resources. However, most of the effort from the state and the private sector focused on large industrial applications [5,8].

Table 2. MoEE Generation Plans 2007–2027 (GWe).

Year	Pre 2007	2007–12	2012–17	2017–22	2022–27	Total	Total (%)
Thermal	18.936	6.550	11.900	10.450	13.000	60.836	79.4
Hydro	2.783	0.064	0.032	-	-	2.879	3.8
Wind	0.225	1.600	2.980	2.500	0.500	7.805	10.2
Solar-thermal	-	0.140	-	-	-	0.140	0.2
Nuclear	-	-	1.000	2.000	2.000	5.000	6.5
Total	21.944	8.354	15.912	14.950	15.500	76.660	100

In general, the private industrial applications of solar power are thermal systems for water heating. According to Mobarak [23], there are three solar thermal systems utilized in Egypt. Two of them are flat-plate solar collectors, including solar water heating systems and integrated solar water heating systems. The third is a parabolic collector solar system. Most of these systems are imported, although solar hot water systems have been manufactured in Egypt since the early eighties [23,24]. Also, concentrated solar power (CSP) projects are large-scale industrial projects that are employed in Egypt for industrial productions of electricity [10]. Other large industrial solar systems include generation of electricity from ground-mounted large-scale systems, which include photovoltaic panels mounted on fixed or movable tilted structures.

Currently, the utilization of solar systems in residential buildings is very limited and only exists in the form of solar collectors used for individual domestic water heaters. A typical system comprises a 150-liter tank, a 2 m^2 solar collector, and a 3-kW electric backup heating element. Most of these water heater units have been installed in state-owned new developments in new cities in the desert. Some hotels use several units of the same system, particularly in remote tourist resorts.

4. Small residential solar system (SRSS)

A small residential solar system is like an industrial ground-mounted system but with a much smaller matrix of photovoltaic panels mounted on a tilted roof of a building or a tilted structure on top of a residential building. Its installation is easy and does not require additional areas for installation. As an additional advantage, a small residential solar system also acts as an additional layer of insulation on the roof of the building. Installation of small residential solar systems on tilted structures offers the best options because the systems could be installed facing the preferred direction and optimum tilt angle. Advanced technologies offer more flexible motorized systems to allow for changing the tilt angle and move the panels to face the sun path during the day to maximize the exposure to the radiation. They can also be installed on sloped roofs and vertical surfaces facing preferred directions. Technological improvements in materials and design resulted in the availability of the panels in several colours and forms, including solar tiles, bifacial solar panels, and transparent solar modules [15,16,19].

The electricity generated by the system could be used directly by the occupants of the building for their everyday needs. It is advisable in this case to consider electricity storage facilities to cater for the times when the generated electricity is less than the consumption, such as at night or on cloudy days. Alternatively, it could be connected directly to a low-voltage grid through an inverter, in which case electricity storage is not needed. Three possibilities are illustrated in **Figure 3** [15].

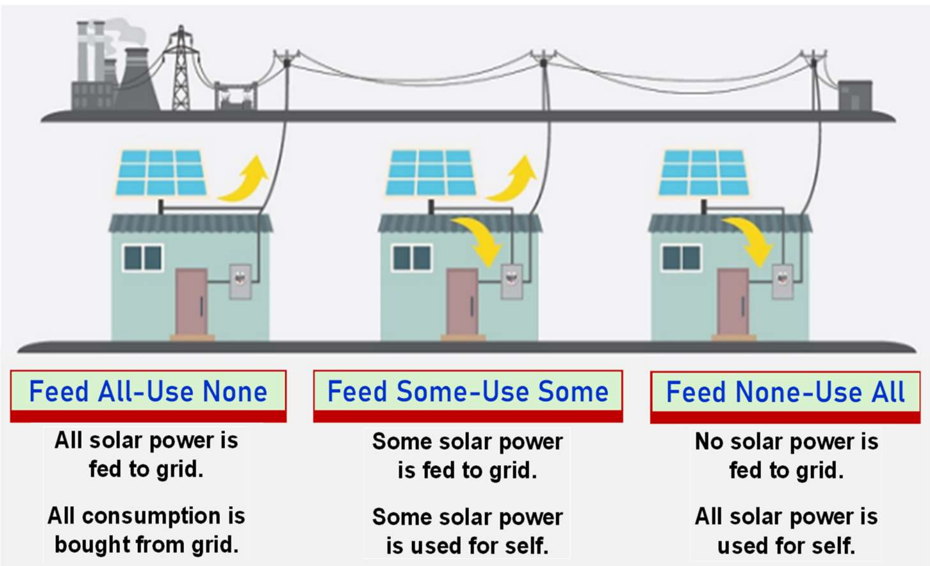


Figure 3. Interaction of solar system with the power grid, adapted from [ESMAP 2021]. License: Creative Commons Attribution CC BY 3.0 IGO

5. Discussion

The amount of solar energy produced from a PV system, regardless of its technology generation, is proportional to the amount of sun irradiation received by the system. The exposure to enough sun irradiation, in turn, depends on the geographical location (particularly longitude and latitude) and the season or the time of the year. Therefore, this section starts with highlighting the advantage of Egypt's geographical location. Then the discussion on quantifying the potentials of SRSS in Egypt is provided. This is followed by a case study on a typical Egyptian residential building to illustrate the initial design of an SRSS, including deciding on the orientation of the system, its optimum tilt angle, and sizing the SRSS system.

5.1. Egypt's geographical location

Egypt has a strategic location in Africa and the Middle East. Most of the country is in northeastern Africa and is extended into Southwest Asia via its Sinai Peninsula. Historically, it was connecting the main old three continents: Africa, Europe, and Asia. The latitude and longitude of the centre of Egypt are 26°15′ N and 30°20′ E. Egypt has an area of just over one million square kilometres, 6% of which is urbanised and populated. The rest is mostly flat, open, sunny deserts [25].

5.2. Quantifying the potentials of SRSS in Egypt

The geographical location determines the climate of a country, city, district, or property. Due to its unique location and climate, Egypt is considered one of the Sun Belt countries, which has great solar potential, as can be seen in **Figure 4**. The amount of annual and daily global solar irradiation should be considered and analysed to decide on the feasibility of using solar power as an alternative sustainable source of energy in a specific location, city, or country.

In addition to the solar system's capacity, type, and technology, the amount of solar energy produced in a full cycle of one day depends on many other factors. However, there are three factors that are most important. The first is the orientation of the system (facing east, west, north, and south). The second is the tilt angle of the system. The third is the number of sunshine hours daily and annually. Clearly, the latter cannot be altered, although it should be considered in the initial stage of the decision-making. The correct choice of the orientation and the tilt angle are, however, crucial in getting the maximum possible power output.

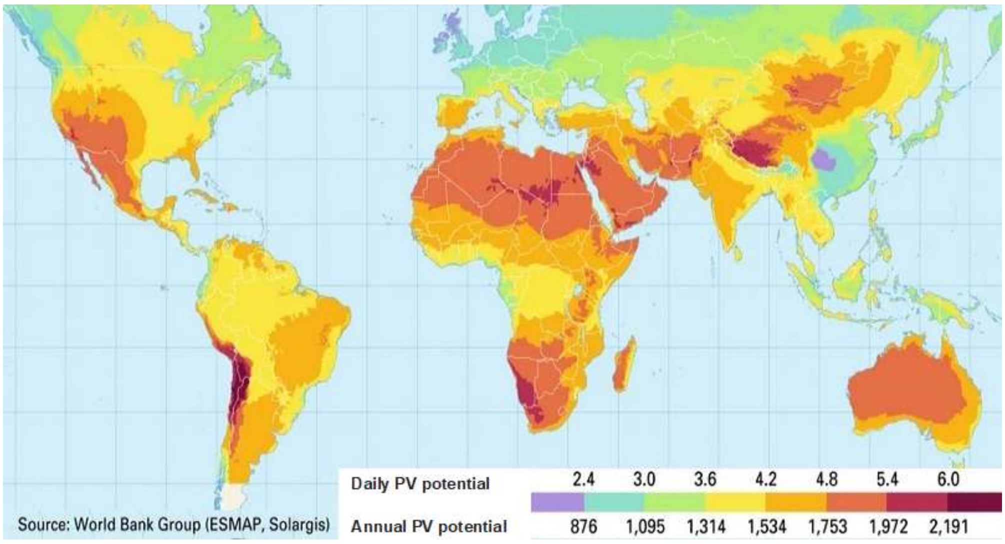


Figure 4. Daily and annual PV power potential in the world (kWh/m^2) [ESMAP, Solargis].

In 1991, a solar atlas for Egypt was issued, confirming the massive potential for solar energy production. It highlighted that the sunshine is in abundance with plenty of sunshine, and the annual direct normal irradiation (DNI) density ranges from 1700 to 3000 kWh/m^2, as can be seen in **Figure 5**. These solar credentials resulted in the technical projection of a potential solar-thermal electricity generation of more than 70 petawatt-hours (PWh) [14].

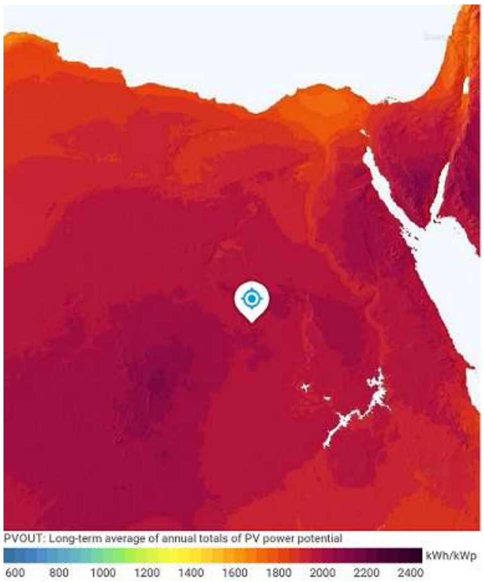


Figure 5. Distribution of annual solar DNI in Egypt (kWh/m2) [ESMAP, Solargis].

The number of sunshine hours per day is more in summer than winter and varies according to the location and geography of a place. The potential of producing solar power using a specific solar system is greater for locations exposed to longer hours of sunshine, as the longer the exposure to sunshine, the more the power output.

Egypt enjoys long hours of daylight around the year, as can be seen in **Figure 6**, with an average of more than 12 h and a maximum of 14 h in June. Sunshine is around for most of the daylight hours. The average hours of sunshine are 9.4 h per day, with a maximum of 11.9 h recorded in June. Except for January and December, all days in Egypt have more than 8 h of sunshine. The annual value is a massive total of more than 3440 h of sunshine per year out of possible 4200 h of daylight. As such, the daily and total hours of sunshine in Egypt indicate great potential for generating photovoltaic electricity from solar radiation.

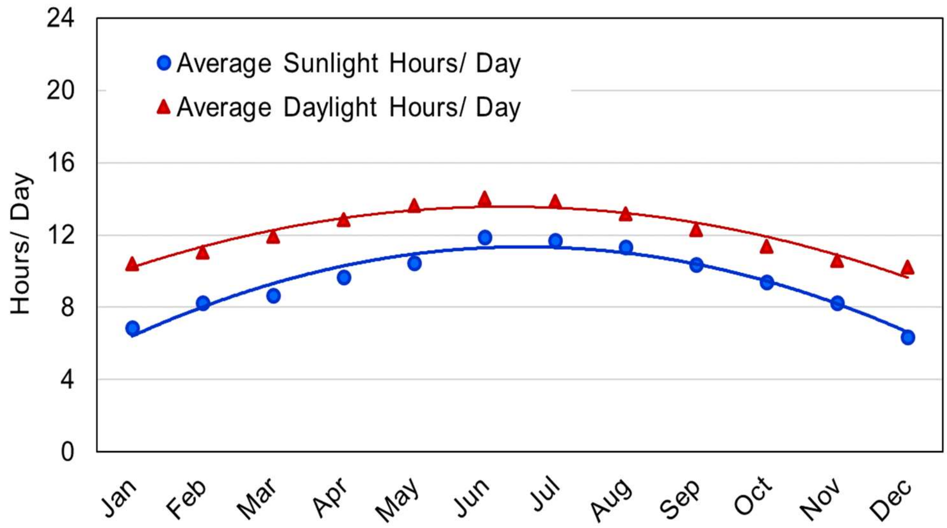


Figure 6. Sunshine hours per day in Egypt.

5.3. Case study: Typical Egyptian residential building

The assessment of the potential of an SRSS installed on the roof of a residential building in Egypt requires information about its location, the number of occupants, their monthly or yearly electricity consumption, and the size of the roof, particularly the area available for installation, which should be free from other facilities.

The mode of residential buildings in Egypt is a 4- or 5-story building. This is the maximum practical height to avoid the need to install an elevator. Such buildings would have a floor area of about 120 to 150 m^2 with a total residential area of about 600 m^2 and have a capacity to accommodate 30 people on average. A typical building of these specifications is considered for illustrating the potential of an SRSS system and deciding on key design aspects, including 1) the best orientation of the SRSS, 2) the optimum tilt angle, and 3) the required size of the system.

5.3.1. Orientation of the SRSS

Proper design of an SRSS requires deciding on the best direction of the panels, at which they are exposed to the maximum irradiation. Using data from the site, irradiation data, and information about the system, the potential of generated power could be calculated per m^2 of the panel or per a prefabricated commercial system, which could be manufactured of a specific size. It could be calculated for a specific period but is usually calculated per day, per month, or annually. To decide on the best direction, the initial calculation was based on the longitude and latitude of Egypt, assuming that the panels are mounted vertically on the face of the building. The results for systems facing North, East, West, and South are shown in **Figure 7**.

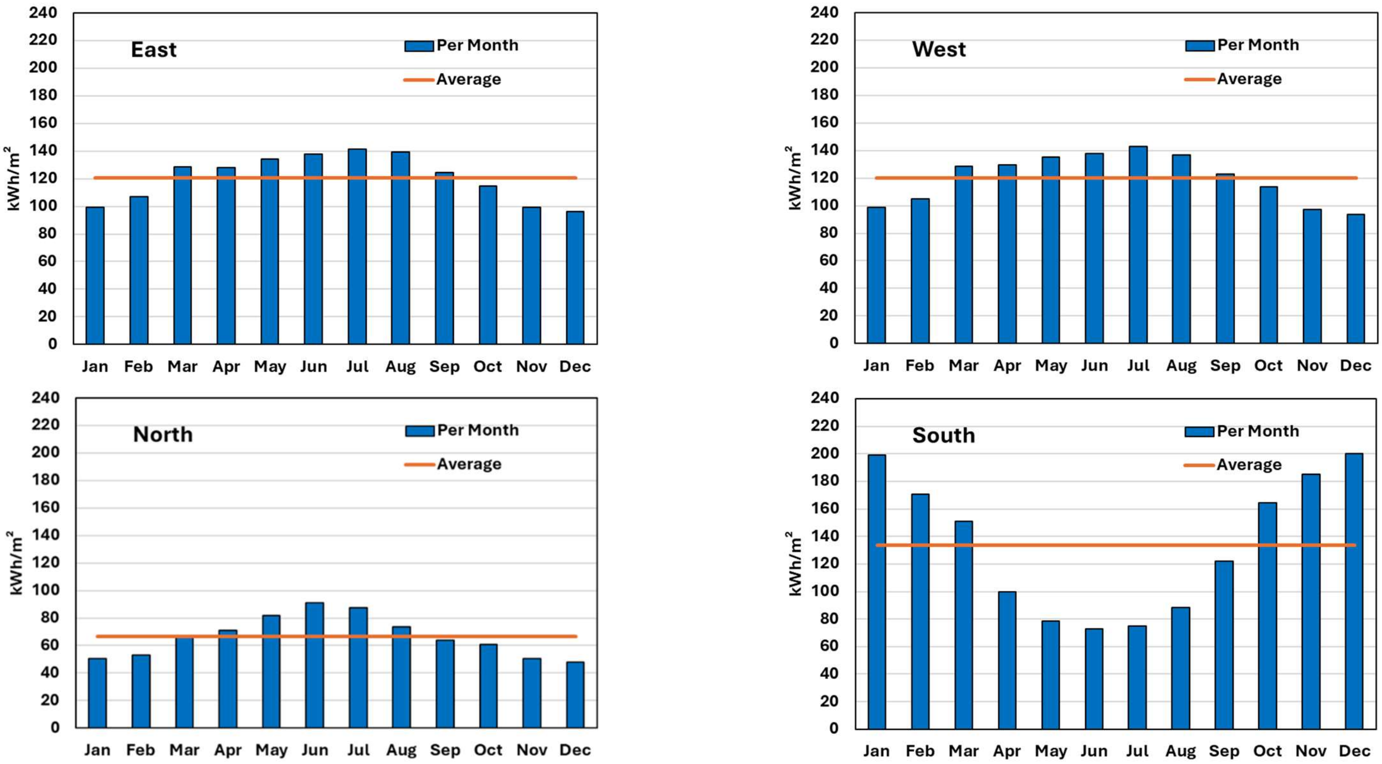


Figure 7. Solar radiation on SRSS facing East, West, North and South.

Comparing the results of solar energy potential for the North, East, West, and South indicated that the south side has the highest average irradiation, at 133 kWh/m^2 per month and a total annual average of about 1600 kWh/m^2. This would have been expected, as facing the Equator offers more exposure to sunlight. However, the south-facing system might not be the best solution because the received irradiation is the lowest during the peak consumption in hot summer months in Egypt, when air-conditioning systems are operating for long hours in the summer.

The higher irradiation in winter compared to that in summer for the south-facing side (facing equator) could be explained using solar motion geometry. The most important factor affecting solar exposure in any location on earth at a specific time is the position of the sun in the sky, which is a function of both the time and the geographic location. The sun appears to move along a circular path across the sky. This sun path depends on the geographic latitude, hemisphere side, and season. For a location in the northern hemisphere, as in the case of Egypt, the winter sun rises in the southeast and sets in the southwest. Therefore, during the day, the sun is always on the south side, hence the higher irradiation in winter on the south-facing side [26–29].

The next highest potential was obtained from the east side, which recorded an average monthly irradiation of 121 kWh/m^2 and a total annual average of more than 1450 kWh/m^2. Comparing the options, it is suggested that the SRSS should be installed facing east and south if the area permits. However, the East would be a priority. It could be noticed also that the West results could be considered as good as the East. As such, the panels could also be installed in the west direction if there were restrictions on site to install in the east and/or south directions.

5.3.2. Optimum tilt angle

Once the best orientation is decided, which for our case is a system facing east direction, the optimum tilt angle should be identified. Using the irradiation data for the east-facing system, the potential solar power at different tilt angles is calculated. For the sake of simplicity, a 1 kWp system is assumed.

The results of the photovoltaic electricity (in kWh) delivered by a 1 kWp system are shown in **Figure 8** for different tilt angles. For example, at 15°, the average output is 144 kWh per month. The corresponding values for each tilt angle are presented in **Figure 9**. It could be suggested that the best tilt would be an inclination between 0° and 15° for this site. It could be argued that such a small inclination would require a large area for installation. Tilt angles close to the vertical will require less area but would have inferior power generation potential. Practically, the results showed that an inclination up to 30° would still produce decent photovoltaic electricity.

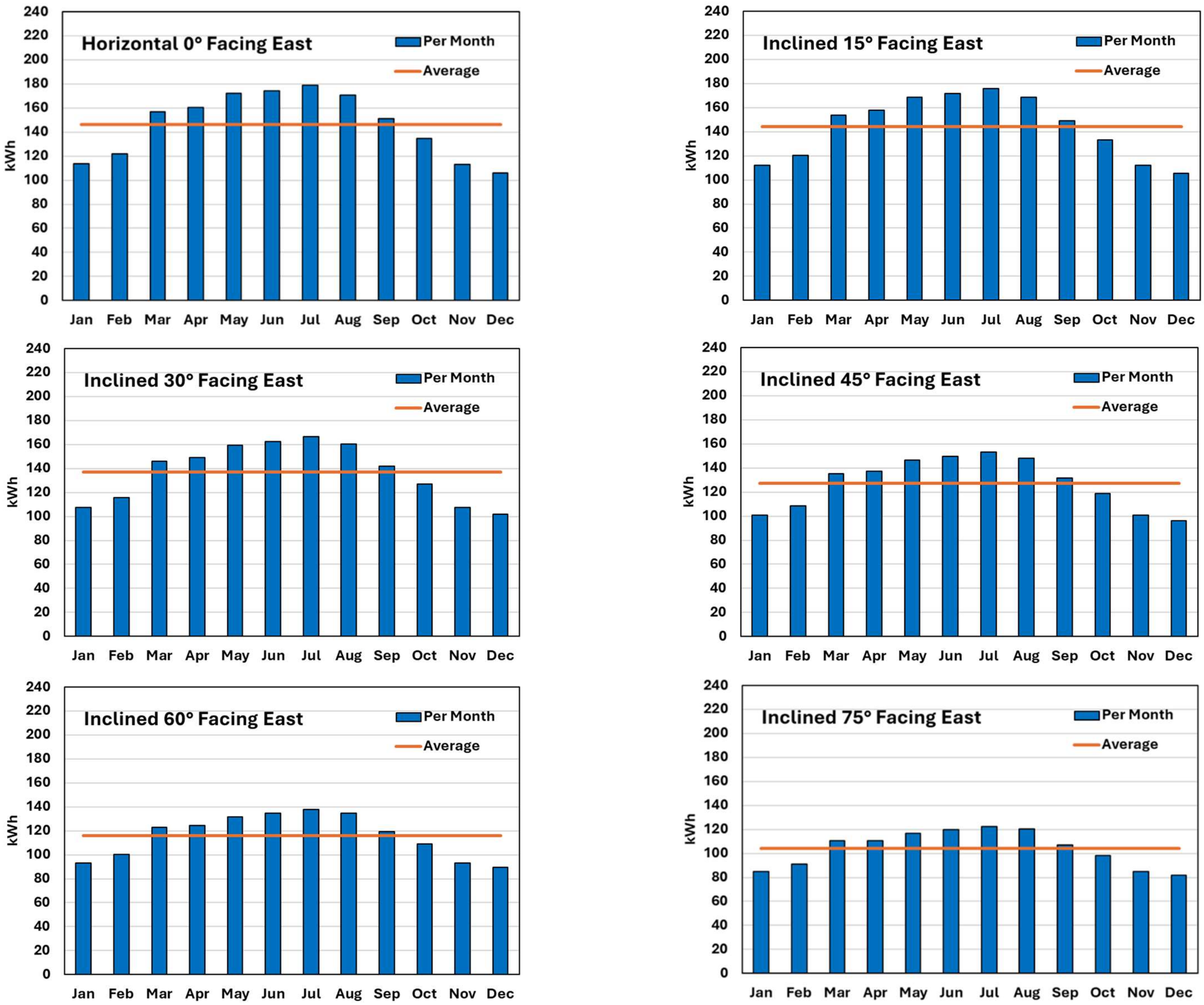


Figure 8. Photovoltaic electricity delivered by 1kWp PV SRSS.

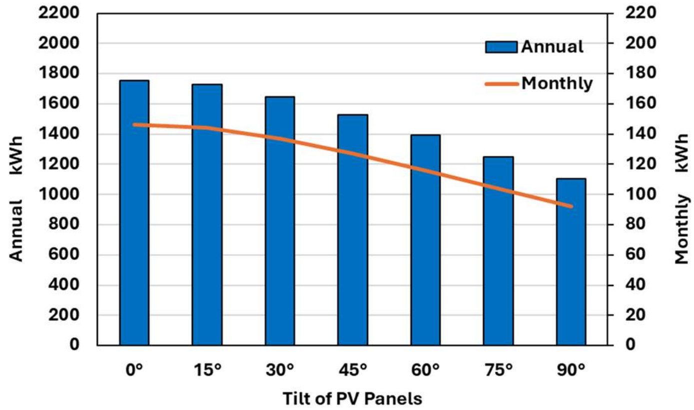


Figure 9. Effect of tilt angle on PV electricity delivered by 1kWp SRSS.

5.3.3. Size of SRSS

The final stage of the design is to decide the size of the SRSS. Taking into consideration the average per-capita electricity consumption in Egypt, the size of the SRSS could be decided. This is currently at 1500 kWh of electricity per year. Thus, for the building under consideration, of about 30 occupants, a total of 45,000 kWh of electricity is needed per year.

Our proposed SRSS is oriented facing the east with an optimum tilt of 15°. Thus, the expected output from a 1 kWp system is 144 kWh per month, on average. The annual total output of this system would be 1730 kWh, meaning a system with 26 kWp will be needed. Such a system would fit easily on the roof of that building, with ample space remaining for air circulation of the SRSS panels and other facilities to be installed on the roof, if needed.

6. Conclusions

This paper highlighted the huge potential for solar energy applications in Egypt, with a focus on small system applications in residential buildings.

This research contributes to promoting the utilization of solar power and the application of small residential solar systems (SRSS) to generate cleaner energy in Egypt. The system not only has a great potential to enable Egypt to close the gap between its produced energy and people's demand but also could help Egypt meet its national and international obligations in reducing emissions.

A case study was used to illustrate the initial design of an SRSS for a typical residential building in Egypt. It provided easy and straight-forward procedures for determining the main parameters of a SRSS, including the capacity of the system, its orientation, and the optimum tilt angle of the solar panels. It also showed that a properly designed SRSS could produce enough electricity to surpass the consumption of the residents of a typical residential building in Egypt.

The implication of implementing the outcome of this research could be significant in helping the country to realise its solar power potentials. If properly regulated, financed, and managed, the utilisation of SRSS in residential buildings in Egypt could provide the country with a sustainable and affordable renewable source of energy.

7. Recommendations

Considering the great potential of utilising SRSS in Egypt, it is recommended that installations of residential solar systems should be made an attractive alternative for homeowners and investors. This could be achieved by implementing the following recommendations.

- Introduce a financial structure that is mainly subsidized to provide the population with easy and adequate access to financial support for solar energy.
- Create a competitive market by encouraging investors from the private sector to invest in designing and manufacturing affordable SRSS of different sizes to accommodate the needs of old buildings and new developments.
- Implement and improve the existing policies to require all new residential and commercial buildings of certain sizes to install certain number of solar units proportional to the size of the building and the number of occupants.

8. Limitations and further research

The focus of this research was on highlighting the importance of small residential solar system (SRSS) for Egypt to realize its great solar potential. Mainly, to close the gap between its produced energy and the demand of its growing population. However, due to the lack of reliable data and vital information on social and economic aspects, it was not possible to conduct a complete life cycle assessment of the proposed system. This could be addressed in future research, once the required information is made available.

Furthermore, the economical affordability of the system could be investigated, including viable proposals for financial funding for installing the system based on targeted profit for investors and property developers.

In addition, further research could also include optimizing the design of SRSS for specific geographical governorates in Egypt.

Acknowledgments: The author would like to acknowledge that some of the solar data used in this research was generated using Global Solar Atlas 2.0 application, which is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP).

Conflict of interest: The author declares no conflict of interest.

Nomenclature

kW	kilowatt (thousand watt)	kWh	kilowatt-hour
PV	photovoltaic	kWp	kilowatt-peak of a PV system
MW	megawatt (million watt)	MW/c	per capita installed power
GW	gigawatt (billion watt)	GWe	gigawatt-electric (billion watt)
PW	petawatt, (1015 watts)	BIPV	building integrated photovoltaic(s)
RE	renewable energy	SRSS	small residential solar system(s)

References

1. Suzuki E. World's population will reach ten billion by 2050. World Development Indicators. World Bank; 2019.
2. World Bank. Urbanization reviews: Urban development overview. Available online: https://www.worldbank.org/en/topic/urbandevelopment/publication/urbanization-reviews (accessed on 22 September 2024).
3. Tadros W, Naguib S, Wellenstein A, et al. Demographic Trends and Urbanization. Available online: http://documents.worldbank.org/curated/en/260581617988607640 (accessed on 22 September 2024).
4. Goujan A, Alkitkat H, Lutz W, et al. Population, and human capital growth in Egypt projections to 2051. Workshop on population, human capital and water in Egypt; 2007.
5. Comsan MNH. Solar energy perspectives in Egypt. In: Proceedings of the 4th Environmental Physics Conference; 2010.
6. International Energy Agency (IEA). Energy system of Egypt. Middle East report. Available online: https://www.iea.org/countries/egypt (accessed on 22 September 2024).
7. Trieb F. Concentrating solar power for the Mediterranean region, MED CSP. German Aerospace Center (DLR); 2005.
8. Salah SI, Eltaweel M, Abeykoon C. Towards a sustainable energy future for Egypt: A systematic review of renewable energy sources, technologies, challenges, and recommendations. Cleaner Engineering and Technology. 2022; 8(100497): 1-30.
9. Patlitzianas KD. Solar energy in Egypt: Significant business opportunities. Renewable energy. 2011; 36(9): 2305-2311.
10. Elshazly RM. Feasibility of concentrated solar power under Egyptian conditions. Renewable Energy & Energy Efficiency for the MENA Region [Master's thesis]. Cairo University & University of Kassel; 2011.
11. Badr A. Desalination sustainability—The need to think again. Towards a Sustainable Water Future. In: Proceeding of the OICWE 2020; 2021.
12. Chaichan MT, Kazem HA. Water solar distiller productivity enhancement using concentrating solar water heater and phase change material (PCM), Case Stud. Therm. Eng. 2015; 151–159.
13. Tan YZ, Wang H, Han L, et al. Photothermal-enhanced and fouling-resistant membrane for solar-assisted membrane distillation. Journal of Membrane Science. 2018; 565: 254-265. doi: 10.1016/j.memsci.2018.08.032
14. Li R, Zhang L, Shi L, et al. MXene Ti3C2: An Effective 2D Light-to-Heat Conversion Material. ACS Nano. 2017; 11(4): 3752-3759. doi: 10.1021/acsnano.6b08415
15. Energy Sector Management Assistance Program (ESMAP). From Sun to Roof to Grid: Distributed PV in Energy Sector Strategies. Technical Report 017/21. Washington, DC: World Bank; 2021.
16. Goetzberger A, Hoffman VU. Photovoltaic Solar Energy Generation. Springer-Verlag; 2005. doi: 10.1007/b137803
17. Li Q, Monticelli C, Kutlu A, et al. Feasibility of textile envelope integrated flexible photovoltaic in Europe: Carbon footprint assessment and life cycle cost analysis. Journal of Cleaner Production. 2023; 430(139716): 1-12. https://doi.org/10.1016/j.jclepro.2023.139716
18. Vassiliades C, Lau K, Moiseos R, et al. A climate sensitive design approach to BIPV: Investigating the nexus between solar energy and thermal comfort in cities in Sweden and Cyprus. Building and Environment. 2023; 243: 110681. doi: 10.1016/j.buildenv.2023.110681
19. Zhou Z, Yuan Z, Yin Z, et al. Progress of semi-transparent emerging photovoltaics for building integrated applications. Green Energy & Environment. 2024; 9(6): 992-1015. doi: 10.1016/j.gee.2023.05.006
20. Gholami H, Røstvik HN, Müller-Eie D. Holistic economic analysis of building integrated photovoltaics (BIPV) system: Case studies evaluation. Energy and Buildings. 2019; 203(109461). doi: 10.1016/j.enbuild.2019.109461
21. Li Q, Monticelli C, Zanelli A. Life cycle assessment of organic solar cells and perovskite solar cells with graphene transparent electrodes. Renewable Energy. 2022; (195): 906-917. doi: 10.1016/j.renene.2022.06.075
22. Li Q, Li T, Kutlu A, et al. Life cycle cost analysis and life cycle assessment of ETFE cushion integrated transparent organic/perovskite solar cells: Comparison with PV glazing skylight. Journal of Building Engineering. 2024; 87(109140): 1-16. doi: 10.1016/j.jobe.2024.109140
23. Mobarak AM. Solar and wind energy. In: Egypt: the present and the future, 3rd ed. Cairo: Faculty of Engineering e Cairo University; 2008.
24. Elshafey S, Shehadeh M, Bayoumi A et al. Solar thermal power in Egypt. In: Proceeding of the 2018 IEEE Industry Applications Society Annual Meeting (IAS); 2018.
25. Wikipedia. Geography of Egypt. Available online: https://en.wikipedia.org/wiki/Geography_of_Egypt (accessed on 22 September 2024).

26. Khavrus V, Shelevytsky I. Geometry, and the physics of seasons. Physics Education. 2012; 47(6): 680-692.
27. Wikipedia. Position of the Sun. Available online: https://en.m.wikipedia.org/wiki/Position_of_the_Sun# (accessed on 22 September 2024).
28. Khavrus V, Shelevytsky I. Introduction to solar motion geometry based on a simple model. Physics Education. 2010; 45(6): 641-655. doi: 10.1088/0031-9120/45/6/010
29. Jenkins A. The Sun's position in the sky. European Journal of Physics. 2013; 34(3): 633. doi: 10.1088/0143-0807/34/3/633

Building Engineering 2024, 2(2), 1342.
https://doi.org/10.59400/be.v2i2.1342

Article

Evaluating the role of consultants in assessing functional feasibility and reliability of buildings: A case study in Banda Aceh

Hafnidar A. Rani[1,*], Mahdi Syahbana[1], Epi Noviana[1], Muhammad Hafidz Mubarak[2], Muhammad Shafly Aqsha[3]

[1] Department of Civil Engineering, Universitas Muhammadiyah Aceh, Banda Aceh 23245, Aceh, Indonesia
[2] Department of Information Technology, Universitas Ubudiyah Indonesia, Banda Aceh 23231, Aceh, Indonesia
[3] Department of Computer Science, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Johor, Malaysia
*** Corresponding author:** Hafnidar A. Rani, hafnidar.ar@unmuha.ac.id

CITATION

Rani HA, Syahbana M, Noviana E, et al. Evaluating the role of consultants in assessing functional feasibility and reliability of buildings: A case study in Banda Aceh. Building Engineering. 2024; 2(2): 1342. https://doi.org/10.59400/be.v2i2.1342

ARTICLE INFO

Received: 2 April 2024
Accepted: 19 June 2024
Available online: 2 July 2024

Abstract: The assessment of building reliability is a critical aspect of the functional feasibility system, as outlined in the 1998 Technical Instructions of the Directorate General of Human Settlements. These assessments typically encompass architectural, structural, and utility criteria. This research aims to understand the role of consultants in evaluating the functional feasibility of buildings in Banda Aceh. Purposive sampling was employed with 11 respondents, considering factors such as education, legal, and technical expertise. Data analysis involved factor analysis using the KMO-MSA method and descriptive analysis using SPSS software. The results reveal that consultants play a crucial role in assessing the functional feasibility of buildings, particularly in terms of skill competency, integrity, and professionalism, with a significant emphasis on the suitability of the function and specifications of the requested buildings. Moreover, the legal factor variable emerges as pivotal in consultants' activities, ensuring compliance with statutory regulations. This study underscores the importance of consultants in ensuring building reliability and adherence to stipulated provisions.

Keywords: consultants; functional feasibility; building reliability; factor analysis; statutory regulations; building assessment

1. Introduction

The issue of post-construction building reliability has garnered significant attention worldwide, considering its paramount importance for completed structures intended for use [1]. Building reliability encompasses various essential aspects mandated by building regulations, such as the Building Law [2], which includes requirements related to physical strength, comfort, utility, and accessibility. Architects in different countries employ diverse methods to conduct reliability testing on buildings, reflecting the global concern for ensuring structural integrity and safety [3].

In Indonesia, building reliability assessments are governed by national regulations. According to the 1998 Directorate General of Human Settlements Technical Instructions [2], reliability assessments are categorized into architectural, structural, and utility criteria. Despite these technical guidelines providing a basis for categorizing buildings as reliable, less reliable, or unreliable, there is a notable gap. The guidelines do not offer a formula for concluding the overall reliability value of a building based on the results of each group's examination [4].

Administrative legal regulations concerning building reliability in Indonesia are part of the mandate of law [2]. This law requires the fulfillment of several components: a Building Construction Permit (IMB), a Functional Feasibility Certificate (SLF), the involvement of a building expert team (TABG), and comprehensive building data collection. Building reliability testing is an integral part of these processes. Technically, such testing ensures that the building structure can handle various loads, both planned and unexpected, and withstand environmental hazards such as landslides, water intrusion, earthquakes, strong winds, and tsunamis [5].

While previous studies have explored various aspects of building reliability, there is a significant research gap in understanding the specific role of consultants in this process. This study aims to fill that gap by focusing on the indicators of consultants' roles in functional feasibility testing activities and evaluating their contributions in the context of Banda Aceh. The research addresses two main questions: What are the indicators of the consultant's role in testing the functional feasibility of buildings in Banda Aceh? What is the role of consultants in these testing activities?

The study reviewed buildings that have been functioning for at least one year and involved consultants engaged in development projects in Banda Aceh. The assessment focused on identifying indicators of the consultant's role in functional feasibility testing activities. Purposive sampling was used to select respondents, and the questionnaire was distributed exclusively to consultants. Factors considered in this research include educational, legal, and technical aspects.

This research aims to determine the indicators of the consultant's role in testing the functional feasibility of buildings in Banda Aceh and to evaluate their role in these testing activities. By addressing this research gap, the study seeks to provide a clearer understanding of how consultants contribute to ensuring the reliability and functional appropriateness of buildings, thereby enhancing the overall quality and safety of building infrastructure in Banda Aceh.

2. Literature review

Building construction is a building that is used as a public facility, for example, institutional buildings, education, light industry such as warehouses, commercial buildings, and social and recreational areas [6]. The types of buildings in this construction include office buildings, shopping centers, apartments/flats, and schools. Building construction is usually planned by architects and civil engineers, while the materials required are more emphasized on architectural aspects [7].

A consultant is a person or legal entity appointed by a service user who has expertise and experience in building construction projects [8]. Consultants provide advisory services (consultancy services) in certain areas of expertise. So, in providing services, consultants will provide analysis or studies, opinions, or opinions according to their expertise to be decided by the project owner [9].

Project management consultants are a work team that has expertise in managing project management and is tasked with monitoring, controlling, and being involved in the project process [8]. It is hoped that it will be able to overcome and anticipate problems in a development project.

Building feasibility is the condition of a building that must meet predetermined requirements, in this case determined by the government [9]. Building feasibility is a measure of whether the building can be used safely and comfortably or not [10]. Building feasibility is necessary for building maintenance [11].

The legal basis for the functional fitness of a building can vary depending on the legal jurisdiction of a particular country or region [12]. Below are several general legal bases that are often used to determine the functional suitability of buildings.

a) Legal basis for building reliability inspection
  - Law no. 28 of 2002, concerning Buildings [2].
  - Minister of Public Works Regulation no. 29/PRT/M/2006 concerning Guidelines for Technical Building Requirements [13].
  - Government Regulation no. 36 of 2005, concerning Implementing Regulations of Law no. 28/2002 [14].

b) Legal basis for accessibility for persons with disabilities
  - Government Regulation no. 30/PRT/M/2006 concerning Technical Guidelines for Facilities and Accessibility in Buildings and the Environment [15].

c) Legal basis for fire safety
  - Decree of the Minister of Public Works No. 10/KPTS/2000 concerning Technical Provisions for Safeguarding against Fire Hazards in Buildings and the Environment [16].
  - Decree of the Minister of Public Works No. 11/KPTS/2000 concerning Technical Provisions for Fire Management in the City [17].
  - Decree of the Director General of Housing and Settlements regarding Technical Instructions for Fire Emergency Action Plans in Buildings.
  - Minister of Public Works Regulation no. 26/PRT/M/2008 concerning Technical Requirements for Fire Protection Systems in Buildings and the Environment [18].

d) Legal basis regarding licensing and certification requirements
  - Minister of Public Works Regulation no. 25/PRT/M/2007 concerning Guidelines for Certification of Building Functionality [19].
  - Minister of Public Works Regulation no. 24/PRT/M/2007 concerning Technical Guidelines for Building Construction Permits [20].
  - Minister of Public Works Regulation no. 26/PRT/M/2007 concerning Guidelines for Building Expert Teams [21].
  - Minister of Public Works Regulation no. 24/PRT/M/2008 concerning Building Maintenance and Maintenance Guidelines [22].
  - Minister of Public Works Regulation no. 29/PRT/M/2006 concerning Guidelines for Technical Building Requirements [13].
  - Minister of Public Works Regulation no. 16/PRT/M/2010 concerning Technical Guidelines for Periodic Building Inspections [23].

Harisun [10] conducted a study on the certification system for building functionality in Ternate City, North Maluku Province. The research explores the correlation between understanding building functionality certification and the perceived impact of mandatory building functionality certification. Through analysis using the SPSS program, a positive and significant correlation was found. Increased understanding of Ministerial Regulation No. 25/PRT/M/2007 regarding building functionality certification guidelines leads to greater compliance among the community and construction service providers. The influence of understanding building functionality certification is calculated at 17.98%, with the remaining 82.02%

influenced by other unexamined factors.

Furthermore, Rasyid [24] conducted an analysis of building functionality in vertical residential buildings: A case study of the Rusunawa Building in Sleman Regency, Yogyakarta, in 2015. The research findings indicate a significant correlation between the level of building functionality and the satisfaction level of vertical residential building occupants.

Lutfi and Syaifullah [11] analyzed the feasibility of building market buildings in Suka Sari, Bogor, through a building approach in 2020. The Sukasari Market Building was constructed in 1987 and completed in 1990 by the Bogor City Government. The Sukasari Market Building stands on a land area of 1936 m^2 with a building area of 2560 m^2, accommodating 225 merchant stalls. This building serves as one of the infrastructure landmarks in Bogor City, utilized as a trading hub for various services and necessities for the local community.

3. Methodology

Research methods are steps that are owned and carried out by researchers in order to collect information or data and carry out investigations on the data that has been obtained [25]. The research methodology employed in this study aims to provide a clear understanding of the research design, data collection procedures, and data analysis techniques utilized. A questionnaire served as the primary data collection tool, employing a survey method to gather respondents' opinions. The collected questionnaire data were meticulously entered into SPSS version 25 software, assigning predetermined codes to facilitate the subsequent data analysis process.

The study acknowledges the limitation of the small sample size, with only 11 respondents, which may impact the generalizability and realism of the results. Despite this limitation, the findings offer valuable preliminary insights into the role of consultants in assessing the functional feasibility of buildings in Banda Aceh. Future research with a larger sample size is recommended to validate and expand upon these findings.

The data processing phase involved statistical analysis, including factor analysis and descriptive analysis. Factor analysis began with formulating the research problem and identifying the original variables slated for analysis. Subsequently, a correlation matrix was established to examine the relationships among variables. Then we selected a factor analysis method and determined the number of factors to be extracted from the numerous variables. Following factor analysis, descriptive analysis was conducted to provide further insights into the data.

Overall, the research methodology encompassed the systematic tabulation and recapitulation of questionnaire responses, followed by rigorous statistical analysis through factor analysis and descriptive analysis techniques. This comprehensive approach ensured a robust investigation into the role of consultants in assessing the functional feasibility of buildings in Banda Aceh.

4. Results and discussions

The characteristics of the respondents in this research were consultants involved in building construction in Banda Aceh, with a total of 11 respondents. The characteristics of these respondents can be grouped based on gender, age, highest level of education, and length of work. The distribution of characteristic percentages will be shown in **Figure 1**.

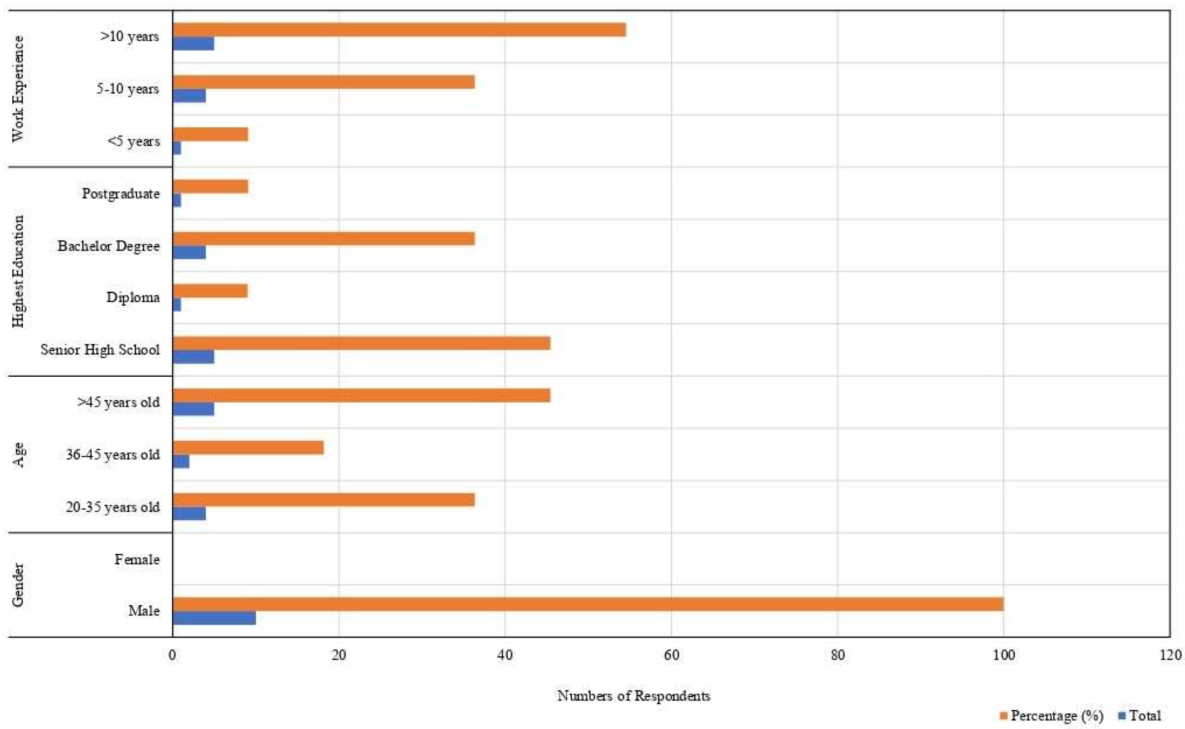


Figure 1. Respondent characteristics.

In factor analysis, there are several variables that will be analyzed so that the suitability of each variable is known, whether it can be processed further using this analysis or not. **Table 1** follows for educational (*X*1), legal (*X*2), and technical (*X*3) variables.

Table 1. KMO and Bartletts's test variable *X*.

KMO and Barlett's test		**Variable**		
		***X*1**	***X*2**	***X*3**
Kaiser-Meyer-Olkin measure of sampling adequacy		0.464	0.635	0.399
Barlett's test of sphericity	Approx. chi-square	20.007	41.911	31.880
	df	15	15	15
	Sig.	0.172	0.000	0.007

Based on the output above for the variable (*X*1) education, it is known that the KMO MSA value is 0.464 < 0.50 with the condition (KMO MSA > 0.50) and the Bartlett's test of sphericity (Sig.) value is 0.172 > 0.050 with the condition (Sig. < 0.05), then the factor analysis in this study was declared invalid and unreliable.

Then for the legal variable (*X*2), it is known that the KMO MSA value is 0.635 > 0.50 with the condition (KMO MSA > 0.50) and the Bartlett's Test of Sphericity (Sig.) value is 0.000 < 0.050 with the condition (Sig. < 0.05), then the factor analysis in this research was declared valid and reliable.

Furthermore, for the technical variable (*X*3), it is known that the KMO MSA value is 0.399 < 0.50 with the condition (KMO MSA > 0.50) and the Bartlett's Test of Sphericity (Sig.) value is 0.007 > 0.050 with the condition (Sig. < 0.05), then the factor analysis in this research was declared invalid and unreliable.

Descriptive analysis is used to determine the frequency of measuring answers to questionnaires in explaining problem solving, based on data from respondents' results. Descriptive analysis is used to present certain characteristics of data from a particular sample. With the help of the SPSS program, the mean value is obtained, which means the average. The results of the descriptive analysis can be seen in **Table 2**.

Table 2. Descriptive analysis.

Variable	Indicator	Mean
*X*1.1	Technical review experts must have a minimum of a Bachelor's Degree in Architecture, Structure and Mechanical, Electrical and Plumbing	2.45
*X*1.2	Has a certificate from the Association of Experts from the Construction Services Development Institute (LPJK)	1.82
*X*1.3	Have a Building Engineering Implementation Permit issued by the local government	2.55
*X*1.4	Have a Business Entity Certificate that is suitable for carrying out functional feasibility studies	2.09
*X*1.5	Has attended various seminars and workshops on building reliability issues	1.64
*X*1.6	Have experience as a construction planner/management for more than 3 years	2.09
*X*2.1	Validate suitability of planning with ABD (As Built Drawing)	2.45
*X*2.2	Validate conformity of ABD with existing	2.55
*X*2.3	Validation of laboratory test results	1.91
*X*2.4	Validation of test inspection results	2.27
*X*2.5	Validation of official memoranda and inspection minutes to stakeholders	2.45
*X*2.6	Validation of the recommendation for the application for the publication of functional eligibility	2.82
*X*3.1	Verify the building area, green, height and borders	1.82
*X*3.2	Field tests related to strength (structure) and soundness	2.27
*X*3.3	Verify the volume requirements required by the agency	2.00
*X*3.4	Observing the suitability of the function and specifications of the requested building	2.91
*X*3.5	Verify the specifications of the materials used in the building	2.36
*X*3.6	Verify Department recommendations for mechanical/electrical elements	2.55

Based on the overall mean value obtained in **Table 2**, the lowest is indicator *X*1.5 (has attended various seminars and workshops on building reliability issues), namely with a mean value of 1.64. This shows that the majority of respondents stated that the *X*1.5 indicator had a low frequency regarding the role of consultants in testing activities for the functional feasibility of buildings in Banda Aceh. Meanwhile, indicator *X*3.4 (observation of suitability of function and specifications of the requested building) has a mean value of 2.91. This shows that the majority of respondents stated that indicator *X*3.4 has a high frequency of the role of consultants in testing activities for the functional feasibility of buildings in Banda Aceh.

Consequently, based on the results of factor analysis and utilizing the Kaiser-Mayer-Olkin Measure of Sampling Adequacy (KMO MSA) method, it is evident that the factor variable for the role of consultants in testing activities for the functional feasibility of buildings primarily comprises the legal factor variable (*X*2). Moreover, the indicators of the role of consultants in testing activities for the appropriateness of building functions in Banda Aceh predominantly align with indicator *X*3.4 (observation of suitability of the function and specifications of the requested building). In this context, the consultant's role encompasses legal aspects pertaining to skill competency as well as behavioral aspects related to integrity and professionalism in executing their duties. Furthermore, the researchers have delineated the role of consultants in testing the functional feasibility of buildings, while a technical review team conducts inspections focusing on two fundamental aspects: the reliability of buildings through architectural, structural, and electrical mechanical examinations of existing buildings. It is imperative to note that the activity of testing the functional feasibility of a building serves as the fulfillment of obligations under statutory regulations. Consequently, consultants play a crucial role in verifying the suitability of functional test results in accordance with the provisions stipulated in regional regulations.

5. Conclusions and recommendations

One limitation of this study is the small sample size, with only 11 respondents participating. This limited questionnaire distribution may result in findings that are not entirely representative or realistic. Future research should aim to include a larger and more diverse sample to improve the reliability and generalizability of the results. By addressing the identified research gap, this study seeks to provide a clearer understanding of how consultants contribute to ensuring the reliability and functional appropriateness of buildings. The findings suggest that consultants play a critical role in verifying the conformity of functional test outcomes with prescribed legal standards, thereby enhancing the overall quality and safety of building infrastructure in Banda Aceh.

From the results of data collection and analysis, several conclusions emerge. Firstly, the descriptive analysis reveals that the indicator "Observation of suitability of the function and specifications of the requested building", focusing on the observation of the suitability of the function and specifications of the requested building, exhibits the highest mean value of 2.91. This indicates a significant emphasis placed on this particular aspect. Secondly, the KMO-MSA results validate the legal variable, affirming its reliability and validity. Consequently, it can be inferred that consultants' roles in testing the feasibility of building functions in Banda Aceh encompass legal aspects, including their proficiency and competency, as well as behaviors reflecting integrity and professionalism. Notably, testing the functional feasibility of buildings aligns with obligations stipulated in statutory regulations, underscoring consultants' responsibility to ensure compliance with regional provisions during this process. Thus, consultants play a crucial role in verifying the conformity of functional test outcomes with prescribed legal standards, thereby contributing to the integrity and reliability of building assessments in the city.

Author contributions: Conceptualization, HAR and MS; methodology, HAR; software, MSA; validation, HAR, MS and EN; formal analysis, HAR; investigation, EN; resources, MHM; data curation, EN; writing—original draft preparation, MS;

writing—review and editing, HAR; visualization, MSA; supervision, MS; project administration, MHM; funding acquisition, HAR. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: We would like to express our sincere gratitude to Mahdi Syahbana, Epi Noviana, Muhammad Hafidz Mubarak, and Muhammad Shafly Aqsha, who contributed to this research project. Their valuable assistance and support were instrumental in the completion of this study.

Conflict of interest: The authors declare no conflict of interest.

References

1. Nitithamyong P, Tan Z. Determinants for effective performance of external project management consultants in Malaysia. Engineering, Construction and Architectural Management. 2007; 14(5): 463-478. doi: 10.1108/09699980710780764
2. Law Number 28 of 2002 dated December 16 2002, on Building, 2002 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/44487/uu-no-28-tahun-2002 (accessed on 22 June 2024).
3. Halil FM, Nasir NM, Hassan AA, et al. Feasibility Study and Economic Assessment in Green Building Projects. Procedia—Social and Behavioral Sciences. 2016; 222: 56-64. doi: 10.1016/j.sbspro.2016.05.176
4. Wuryanti W, Suhedi F. Interpretation of Building Reliability Inspection Results (Indonesian). Jurnal Permukiman. 2016; 11(2): 74. doi: 10.31815/jp.2016.11.74-87
5. Rani HA, Hanif M. Implementation of Fit for Purpose Certification for Public Buildings in Banda Aceh City (Indonesian). Tameh: Journal of Civil Engineering. 2021; 10(1): 9-19. doi: 10.37598/tameh.v10i1.120
6. Rani HA. Construction Project Management (Indonesian). Deepublish; 2016.
7. Rani HA. Project Management Functionality in Construction Project Success (Indonesian). Deepublish; 2021.
8. Sukarta KGN, Tjakra J, Pratasis PAK. The Role of Construction Management Consultant in Building Construction Project (Case Study: Multipurpose Building of Tadulako University, Palu—Central Sulawesi) (Indonesian). TEKNO. 2021; 19: 79.
9. Simanjuntak MRA, Budiman D. Study on the Identification of Factors of Consultant's Role in Testing the Passability of Function after Handover of Construction Work in Bekasi City (Indonesian). Prosiding Seminar Nasional Teknik Sipil. 2019; 285-291.
10. Harisun E. Study of Building Function Certificate System in Ternate City, North Maluku Province (Indonesian). Jurnal Ilmiah Media Engineering. 2013; 3(1): 14-22.
11. Lutfi M, Syaifullah BN. Analysis of the feasibility of the sukasari bogor market building through the building function feasibility approach (Indonesian). ASTONJADRO. 2020; 9(1): 14. doi: 10.32832/astonjadro.v9i1.2726
12. McLeod S. Feasibility studies for novel and complex projects: Principles synthesised through an integrative review. Project Leadership and Society. 2021; 2: 100022. doi: 10.1016/j.plas.2021.100022
13. Minister of Public Works Regulation No. 29/PRT/M/2006 on Guidelines for Technical Requirements for Buildings, 2006 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104487/permen-pupr-no-29prtm2006-tahun-2006 (accessed on 22 June 2024).
14. Government Regulation No. 36/2005, on the Implementation Regulation of Law No. 28/2002, 2005 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/49491 (accessed on 22 June 2024).
15. Government Regulation No. 30/PRT/M/2006 on Technical Guidelines for Facilities and Accessibility in Buildings and the Environment, 2006 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104488/permen-pupr-no-30prtm2006-tahun-2006 (accessed on 22 June 2024).
16. Decree of the Minister of Public Works No. 10/KPTS/2000 on Technical Provisions for Fire Safety in Buildings and Environments, 2000 (Indonesian). Available online: https://jdih.pu.go.id/detail-dokumen/2020/1#div_cari_detail (accessed on 22 June 2024).
17. Decree of the Minister of Public Works No. 11/KPTS/2000 on Technical Provisions for Fire Management in Cities, 2000 (Indonesian). Available online: https://peraturan.infoasn.id/keputusan-menteri-pekerjaan-umum-dan-perumahan-rakyat-nomor-11-kpts-m-2000/ (accessed on 22 June 2024).
18. Minister of Public Works Regulation No. 26/PRT/M/2008 on Technical Requirements for Fire Protection Systems in

Buildings and Environments, 2008 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104475/permen-pupr-no-26prtm2008-tahun-2008 (accessed on 22 June 2024).
19. Minister of Public Works Regulation No. 25/PRT/M/2007 on Guidelines for Building Function Certificate, 2007 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104490/permen-pupr-no-25prtm2007-tahun-2007 (accessed on 22 June 2024).
20. Minister of Public Works Regulation No. 24/PRT/M/2007 on Technical Guidelines for Building Construction Permits, 2007 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104489/permen-pupr-no-24prtm2007-tahun-2007 (accessed on 22 June 2024).
21. Minister of Public Works Regulation No. 26/PRT/M/2007 on Guidelines for Building Expert Teams, 2007 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104491/permen-pupr-no-26prtm2007-tahun-2007 (accessed on 22 June 2024).
22. Minister of Public Works Regulation No. 24/ PRT/M/2008 on Guidelines for Building Maintenance and Maintenance, 2008 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/104476/permen-pupr-no-24prtm2008-tahun-2008 (accessed on 22 June 2024).
23. Minister of Public Works Regulation No. 16/PRT/M/2010 on Technical Guidelines for Periodic Inspection of Buildings, 2010 (Indonesian). Available online: https://peraturan.bpk.go.id/Details/160054/permen-pupr-no-16prtm2010-tahun-2010 (accessed on 22 June 2024).
24. Rasyid YA. Feasibility Analysis of Vertical Residential Buildings (Case Study: Sleman Regency Rusunawa Building, Yogyakarta) (Indonesian). Jurnal Teknisia. 2015; 2: 516-525.
25. Sugiyono. Quantitative, Qualitative and R&D Research Methods (Indonesian). Alfabeta; 2020.

Building Engineering 2024, 2(2), 1247.
https://doi.org/10.59400/be.v2i2.1247

Article

Value-based analysis of the negotiation for the construction of a church dome

Mario Luis Chew Hernández*, **Leopoldo Viveros Rosas, Raúl Gómez Gómez-Tagle**

Department of Industrial Engineering, TeCNM: Tecnológico de Estudios Superiores de Coacalco, Coacalco de Berriozábal 55700, Mexico
*** Corresponding author:** Mario Luis Chew Hernández, mario@tesco.edu.mx

CITATION

Hernández MLC, Rosas LV, Gómez-Tagle RG. Value-based analysis of the negotiation for the construction of a church dome. Building Engineering. 2024; 2(2): 1247. https://doi.org/10.59400/be.v2i2.1247

ARTICLE INFO

Received: 29 March 2024
Accepted: 16 June 2024
Available online: 10 July 2024

Abstract: In the construction industry, the signing of contracts between contractors and clients is a common practice. The entities signing these contacts have vastly different objectives in the context of the project: the contractor is motivated by the achievement of profit, while the client has objectives that can be economic, aesthetic, related to completion time, etc. According to negotiation theory, the greater the difference between the objectives of the sides, the better the contracts that can be achieved in the negotiation. Therefore, the analysis of a contractor-client negotiation in the building industry should be based on a complete understanding of the objectives of the sides. Kenney's Value-Focused Thinking (VFT) provides a framework on which such understanding can be achieved. This paper presents a VFT-based methodology to analyze the contractor-client negotiations in the context of construction projects. The methodology is illustrated by analyzing, in retrospective, the negotiation between a construction company and a client regarding the construction of a dome for a church. The results show the usefulness of analyzing the negotiation from the point of view of the sides' objectives.

Keywords: negotiation; decision analysis; construction

1. Introduction

In the business of constructing houses and buildings, there are specialized entities (contractors) that carry out the actual construction activities and deliver the finished product to a client or buyer. Before starting the building activities, the contractor and client must agree on a contract specifying the characteristics of the work. The contract contents (physical characteristics of the building, materials, delivery time, building price tag, etc.) are settled in a negotiation process between the client and the contractor.

The objectives of the client and contractor in the context of the project are quite different. The main objective of the contractor is economic, so his worries about other negotiation elements (for example, delivery time and building characteristics) derive from the effect of these issues on the profit. In contrast, the client has several essential objectives beside the monetary one, as, even though he prefers to pay less money than more, he is willing to accept a cost increase in exchange for changes in other elements, such as improved aesthetics or a reduction in delivery time. This indicates that, for the customer, cost, aesthetics, and completion time are all essential objectives.

In a negotiation in which several issues (themes) need to be decided, the potential of finding contracts that are convenient for both sides (win-win contracts) depends on the difference in the sides' objectives. The analysis of contracts between clients and contractors in the construction industry, then, must begin with analyzing and structuring the objectives of the parties. Keeney's [1] Value-Focused Thinking, which states that the analysis of a decision situation should begin by structuring and understanding the decision-maker's objectives, provides a framework for analyzing the contractor-client negotiation from the point of view of the parties' objectives.

Regarding related research, Verheij and Augenbroe [2] propose a method for planning architectural, engineering, and construction projects applying collaborative decision-making concepts, and Murtoaro and Kujala [3] provide a framework for dealing with client-contractor negotiations to support the work of professional negotiators. Specific negotiation elements relevant to construction negotiation are treated by Branconi and Loch [4], who deal with the influence of business leaders' philosophies on negotiation proceedings; Koskinen and Mäkinen [5], who analyze the effect of the boundary object (or the interface between the sides) in the final agreement; and Oliveira et al. [6], who study the effect of contractor technical competence on the contracts.

There are several reports of the application of game theory for analyzing construction contracts. Lippman et al. [7] use game theory and the Nash equilibrium concept for managing outsourced projects with cost uncertainty, with Tosselli et al. [8] adding process simulation to these elements and developing an automatized negotiation protocol; Ng and Li [9] design an automated bargaining protocol for contracting suppliers when parent companies are participating in tenders; Shang et al. [10] analyze the distribution of the economic incentives of energy-saving contracts using Rubinstein's game theoretical model; and Tang et al. [11] study the fair sharing of the project risks. Applications of game theory to the analysis of build-transfer-operate projects are shown in Kang et al. [12] for calculating royalties, Zhang et al. [13] for determining the optimal lifetime and concession period, and Bao et al. [14] for identifying the concession period for a project under conditions of incomplete information. Finally, Song et al. [15] develop a bargaining model for setting compensations in road projects that had to be finished early.

Models foreseeing changes or deviations in original plans are shown in Chen and Wang [16], who apply multi-agent concepts to develop a compensatory model for the dynamic scheduling of projects. Badenfelt [17] proposes a framework to address the problems generated when contracts must be adjusted, using risk sharing and social influence theories, and Miranda-Sarmento and Renneboog [18] deal with the renegotiation of public-private deals, highlighting the impact of the strategic behaviors of the parties caused by electoral cycles and changes in the companies strength.

Considerations of non-economic objectives in construction negotiations appear in Kumar et al. [19], who discuss public-private deals for energy projects. Stapper [20] mentions the inclusion of citizens in the negotiations of public projects, showing how citizens' objectives can influence negotiation results. Adebayo and Werker [21] quantitatively model mining companies' benefit-sharing agreements with communities, where the communities' gains of job creation and economic opportunities are balanced by the health risks of the miner's activity, and Jalbert et al. [22] analyze the effect of the risk perception of the owners of the land on which gas lines are to be built on the contracts they find acceptable as the owners balance their payment against the pipe risks.

The research just described, although treating negotiations between sides with objectives of different natures (e.g., economic, environmental, and related to health or security), neither analyzes nor structures the objectives of the parties. This is done by the methodology put forward here to analyze contractor-client negotiations, which is based on applying decision analysis concepts [23,24], and in particular value-focused thinking [1] to the situation. Decision analysis is a discipline dealing with decision-making from a prescriptive-normative point of view, that is, how to make better decisions given the cognitive limitations and the preferences of the decision-maker [25].

2. Negotiation analysis methodology

It is assumed that two sides, the contractor and the client, must reach an agreement on the characteristics, delivery time, and payment for a construction job. The methodology for analyzing the negotiation, based on the steps put forward by Raiffa [26], is described below.

1) Analysis of the objectives of the sides. In this step, each side identifies its objectives and proceeds to divide them into fundamental objectives (objectives that are essentially important) and means objectives (important because they promote other objectives). The objectives are structured into the fundamental objectives hierarchy and the network of means-ends objectives. In case one of the sides has objectives that are non-monetary (for example, the client may have objectives related to the building aesthetics), scales should be constructed to measure the achievement of these objectives, and the trade-off between objectives of different natures must be defined.
2) Definition of the frame of the negotiation. The negotiation frame consists of the issues that need to be settled and the levels they may take. A "contract" is set by selecting a level of each negotiation issue.
3) Development of models mapping the levels of the issues to the fundamental objectives of the negotiating sides. For the contractor, whose fundamental objective is monetary, this model is based on factual knowledge (for example, how much a change in the design or in the target completion time represents in cost). In the case of the client, who may have non-economic fundamental objectives, this model reflects his preference for different issue levels, so his model relies heavily on subjective preferences and value judgments.
4) Using the derived models, the sides' preferences for the possible contracts can be calculated and plotted. From the produced graph, acceptable contracts are identified, and the non-dominated contracts (i.e., contracts for which there is no other contract that is better for both parties) that make up the "efficient frontier" of the problem are pointed out as candidate final contracts.
5) Using concepts of fairness and equity, a contract from the efficient frontiers is selected as the final contract to be agreed by the parts.

3. Application of the methodology to an example

The described steps are applied to a contractor-client negotiation case study that is based on a real-life situation involving one of the authors of this work. The "contractor side" is a construction company, while the "client side" is a committee representing a religious congregation needing a dome for a church. The dome should serve as a roof to cover a square-shaped space of approximately ten meters per side. The committee is made up of five people, representing around one hundred sponsors of the dome purchase.

3.1. Analysis of objectives

For the analysis, the parts are assumed to be monolithic.

3.1.1. Contractor

The contractor's objectives are related to profit and safety. The profit is calculated as the price paid by the client minus the construction costs, so objectives such as "maximize price" and "minimize costs" are identified and arranged into the contractor's fundamental objectives hierarchy (**Figure 1**). The mean objectives, that are valuable for their impact on fundamental objectives, make up the network of mean-end objectives, shown in **Figure 2**. This figure shows, for example, that a way to decrease labor costs is to reduce the number of workers. As it is assumed that the alternatives do not impact the project's safety, only economic objectives are considered going forward.

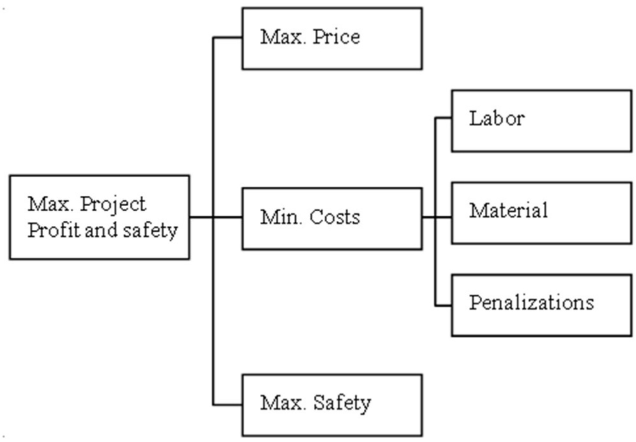


Figure 1. Contractor's fundamental objectives hierarchy.

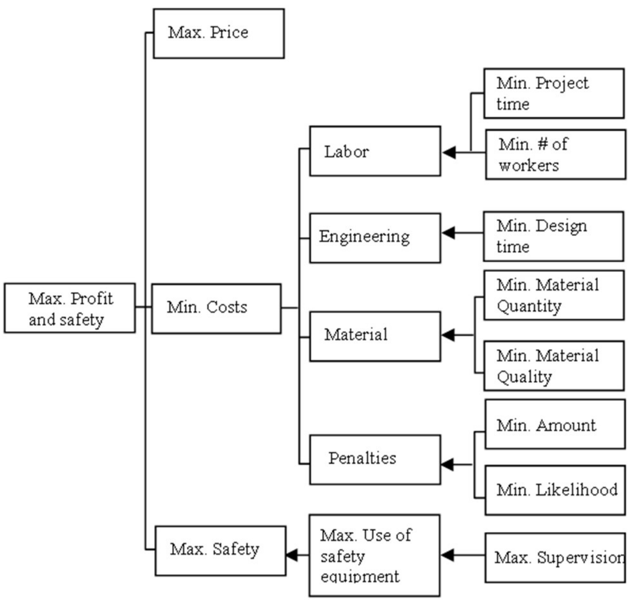


Figure 2. Contactor's mean-ends objective network.

The impact of project decisions on the total cost (called COST) is shown in the influence diagram of **Figure 3**. In these diagrams, rectangles represent decisions, ovals represent uncertain events, and ovals with double edges represent deterministic calculations.

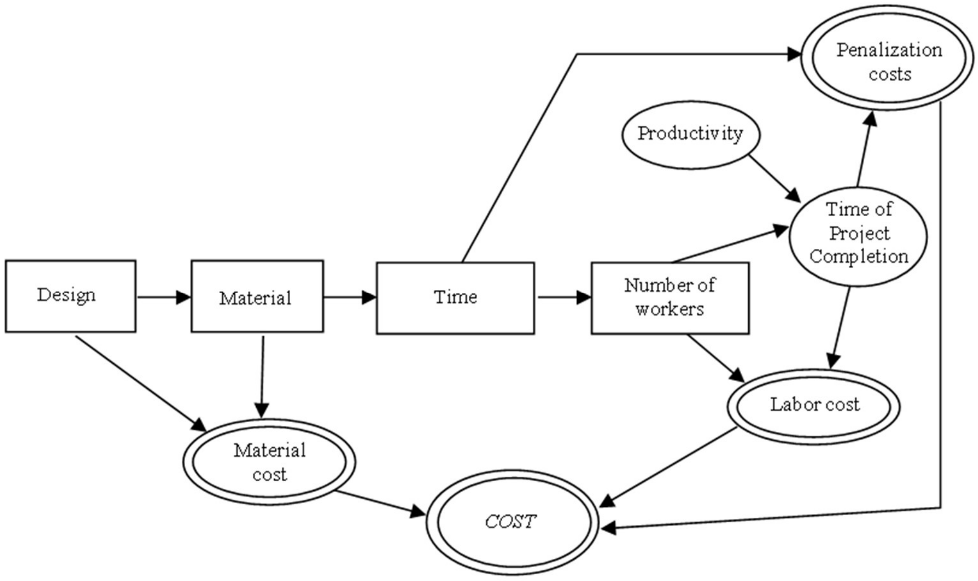


Figure 3. Influence diagram of the total cost.

If price is the monetary amount paid by the client for the building, then the contractor's profit is

$$\text{Profit} = \text{Price} - \text{Cost} \quad (1)$$

Being an early stage in the negotiation, the costs are not calculated in detail but with a simplified model. The total costs are the sum of material and labor costs. Material costs (C_{MAT}) are calculated from the total weight of the material used, which is calculated as volume times density

$$C_{\mathrm{MAT}} = \text{Weight (kg)} \times \text{Unitary material price (\$/kg)} \quad (2)$$

$$\text{Weight (kg)} = \text{Density (kg/m}^3\text{)} \times \text{Area (m}^2\text{)} \times \text{thickness (m)} \quad (3)$$

The labor cost derives from the workers cost (C_{TR}) and manufacturing cost (C_{MAN}), the latter representing the expense of subcontracting part of the work.

$$C_{\mathrm{TR}} = 30 \text{ (day/month)} \times T \times n \times \text{wage (\$/day-worker)} \quad (4)$$

Being n the number of workers, T the project target completion time in months, and wage the daily wage of a worker. The model relating T and n relies on the contractor's expertise. For a given design, the contractor estimates that the completion time for a given number of workers n_0 is T_0 months. With two additional points (n_1, T_1) and (n_2, T_2), a quadratic relationship $T_f(n)$ between completion time and number of workers is assumed.

$$T_f(n) = a \times n^2 + b \times n + c \quad (5)$$

Thus, for a given completion time, the workers cost is given by

$$C_{TR} = 30 \times T \times T_f^{-1}(T) \times \text{wage} \quad (6)$$

Being $T_f^{-1}()$ the inverse function of T_f. C_{MAN} depends on the building design and can be obtained through quotes from companies to be subcontracted. The total building cost is

$$\text{Cost} = C_{\text{MAT}} + C_{\text{TR}} + C_{\text{MAN}} \quad (7)$$

3.1.2. Client

The client's objectives in the context of this negotiation are:

1) Minimize construction time.
2) Maximize the aesthetic qualities of the dome.
3) Minimize the amount of money paid.

These fundamental objectives are structured into the fundamental objectives hierarchy of **Figure 4**.

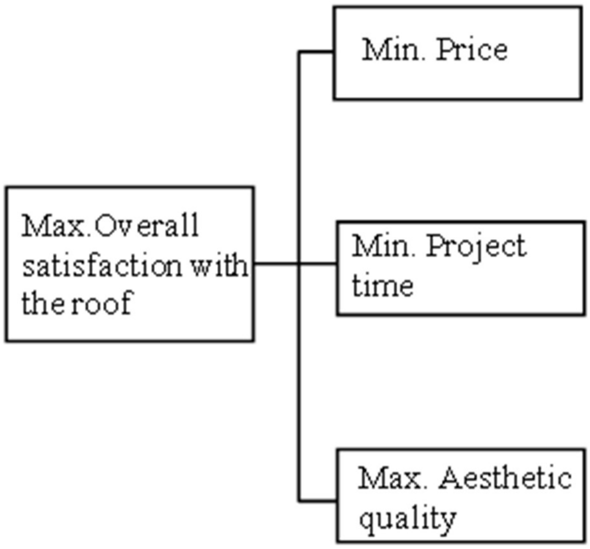


Figure 4. Client's fundamental objectives hierarchy.

These objectives must be quantified to measure how much the client values each contract. The client's utility (U_C) is calculated additively from three elements: U_T construction time utility, U_{CE} aesthetic quality utility, and U_P construction price utility.

$$U_C = k_1 \times U_T + k_2 \times U_{CE} + k_3 \times U_P \quad (8)$$

Equation (8) reflects that the client's bottom line is made up of three dimensions: finishing time, price, and aesthetics. For instance, a given price hike (U_P decreases) can be compensated for by a better-liked design (U_{CE} increases), thus keeping U_C constant and indicating a constant client's satisfaction. In this example, the client's preference for project time is given in **Table 1**.

Table 1. Client's preference for project time.

Level	Description	Utility (U_T)
0	1 to 5 months	1.0
1	5 to 10 months	0.5
2	11 months or more	0

The quantification of the client's preference for the dome aesthetic qualities, requires the measurement of the client feelings with respect to different dome shapes and materials. The candidate dome designs in this problem are sketched in **Figure 5**.

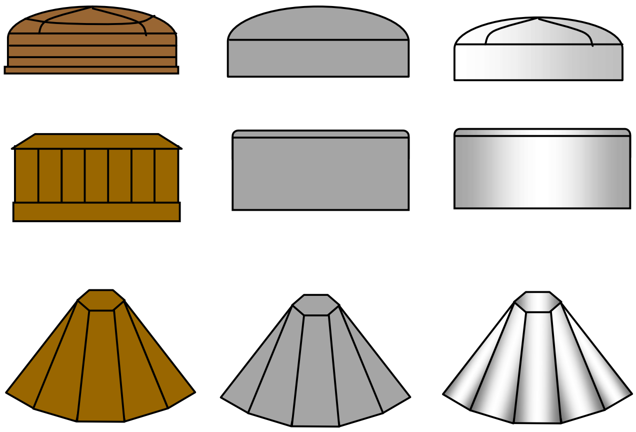


Figure 5. Candidate dome designs.

Three dome shapes are considered (S: Skirt, R: Rectangle and C: Circle) in three materials (W: Wood, C: Concrete and A: Aluminum). To begin the preference quantification, the first task is to get the client to order the nine candidate designs according to his preferences. This task would be simpler if the elements making up a dome design (shape and material) could be treated separately. As an example, let's say that if the material is concrete, the shape preference was found to be:

Skirt ▷ Circle ▷ Rectangle

With "▷" meaning "is preferred to". And, if the material is changed to wood, the preference order for shape changes to

Skirt ▷ Rectangle ▷ Circle

This would mean that the attributes of shape and material are not separable and must be considered together in the preference elicitation. A procedure for doing so is described next, with the notation "SM" being S = Shape and M = Material (e.g., SC = Skirt-Concrete and RW = Rectangle-Wood), used to denote a dome design. First, for each shape, the preference for materials is elicited, let's say the resulting orderings are:

Skirt	SA ▷ SC ▷ SW
Circular	CA ▷ CC ▷ CW
Rectangle	RC ▷ RW ▷ RA

In a similar manner, for each dome material, the client provides his preference for shape; examples of such orderings are:

Aluminum	SA ▷ CA ▷ RA
Concrete	SC ▷ CC ▷ RC
Wood	SW ▷ RW ▷ CW

Next, the client must choose his most and least preferred designs. Let the former be the Skirt of Aluminum (SA) and the latter the Rectangle of Aluminum (RA), then the relation RW ▷ RA and RW ▷ CW imply the preference order.

SA ▷ RW ▷ CW ▷ RA

As RC ▷ RW, CC ▷ RC and CA ▷ CC, then

SA ▷ CA ▷ CC ▷ RC ▷ RW ▷ CW ▷ RA

The location of SC and SW in this list is not completely defined by the elicited preferences of shape and material: according to these, SC is to the left of CC and to the right of SA but its precise location should be elicited directly from the client. If the client prefers SC to CC, but prefers CA over SC, then

SA ▷ CA ▷ SC ▷ CC ▷ RC ▷ RW ▷ CW ▷ RA

By locating SW in a similar manner, the complete ordered list is elicited, as illustrated below.

SA ▷ CA ▷ SC ▷ CC ▷ RC ▷ SW ▷ RW ▷ CW ▷ RA

The method of point allocation can be used to express these preferences quantitatively [23]. **Table 2** shows a likely set of results of this procedure.

Table 2. Client's utility for dome designs.

Order	Notation	Description	Points	U_{CE}
1	SA	Skirt of aluminum	100	1.0
2	CA	Circle of aluminum	80	0.8
3	SC	Skirt of concrete	60	0.6
4	CC	Circle of concrete	50	0.5
5	RC	Rectangle of concrete	45	0.45
6	SW	Skirt of wood	30	0.3
7	RW	Rectangle of wood	12	0.12
8	CW	Circle of wood	10	0.1
9	RA	Rectangle of aluminum	0	0

Finally, the client has preferences for the money he is charged for the dome. The client's utility for price, U_P can be a linear function with a value of one for a price of cero and a value of $-(k_1 + k_2)$ for the maximum monetary amount the client is willing to pay.

3.2. Negotiation frame

The negotiation frame includes the issues whose resolution may affect the fundamental objectives of at least one of the negotiating sides and the possible resolution levels of these issues. The negotiation frame of the worked example case is shown in **Table 3**.

Table 3. Negotiation frame.

Issue	Level
Shape	a) Skirt b) Circle c) Rectangle
Material	a) Concrete b) Aluminum c) Wood
Project completion time	a) 4 Months b) 8 Months c) 12 Months
Price	a) \$35,000 b) \$50,000 c) \$75,000

3.3. Contract plot

The client utility was calculated with the following weights in Equation (8): k_1 =

0.2, k_2 = 0.5, and k_3 = 0.3. The contractor's utility is calculated as his profit, equation 1, divided by 75'000, so to produce utilities on a scale comparable to that of the client's. All combinations of the levels of the issues in **Table 3** can produce 81 different contracts. The contractor's and client's utilities for these contracts are shown in **Figure 6**.

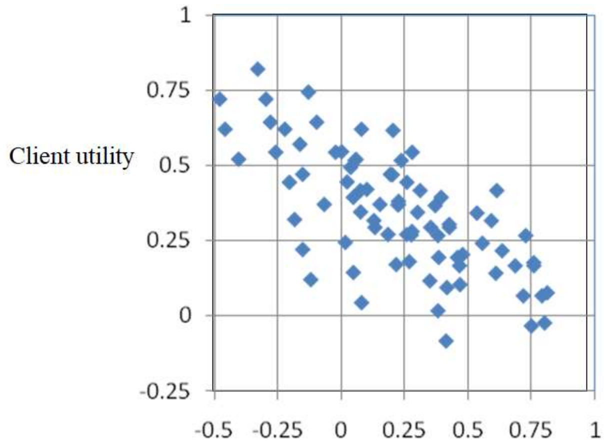


Figure 6. Possible contracts.

The contracts that are non-dominated constitute the efficient frontier (**Figure 7a**); among them, those not lying in valleys make up the "extreme efficient frontier" (**Figure 7b**), which is used as a basis for finding a final contract. **Table 4** shows the contracts on the extreme efficient frontier, where a contract number is used to label each extreme efficient contract.

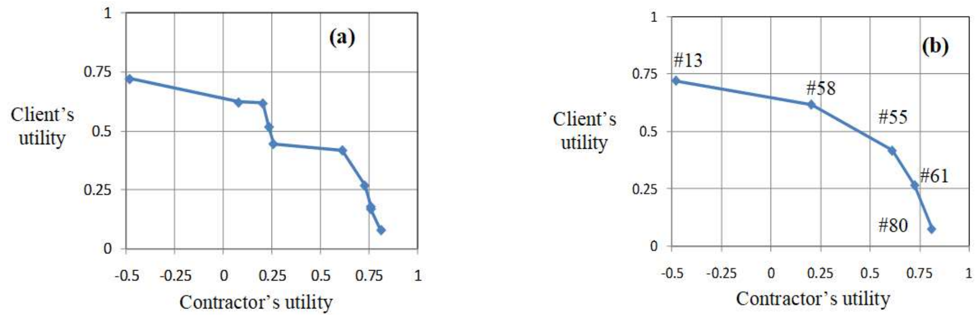


Figure 7. (a) efficient frontier; **(b)** extreme efficient frontier.

Table 4. Contracts on the extreme efficient frontier.

#	Shape	Material	Time (months)	Price ($)	Contractor's utility	Client's utility
80	Rectangle	Wood	8	75,000	0.811	0.078
61	Skirt	Wood	4	75,000	0.726	0.268
55	Skirt	Concrete	4	75,000	0.611	0.418
58	Skirt	Aluminum	4	75,000	0.203	0.618
13	Circle	Aluminum	4	35,000	−0.481	0.722

The contracts on the extreme efficient frontier that are the most beneficial to both sides are those lying the closest to a 45° line in **Figure 7a**. These contracts are labelled #58 and #55 (**Table 5**).

Table 5. Fairest extreme efficient contracts.

#	Shape	Material	Time (months)	Price ($)	Contractor's utility	Client's utility
55	Skirt	Concrete	4	75,000	0.611	0.418
58	Skirt	Aluminum	4	75,000	0.203	0.618

Of these contracts, #55 favors the contractor (his utility is 0.611 against the client's 0.418), and the other favors the client (the utility of the contractor is 0.203 and the client's is 0.618). These contracts can be used as a basis to define more equitable ones: By lowering the price of #55 (favoring the client) and raising the price of #58 (favoring the contractor), equitable contracts #55' and #58' are defined (**Table 6** and **Figure 8**).

Table 6. Final equitable contracts.

#	Shape	Material	Time (months)	Price ($)	Contractor's utility	Client's utility
55'	Skirt	Concrete	4	$65,000	0.511	0.455
58'	Skirt	Aluminum	4	$80,000	0.469	0.515

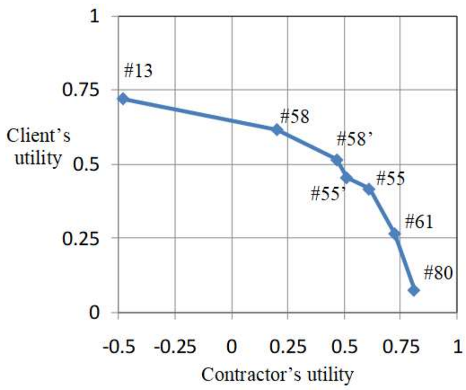


Figure 8. Final equitable contracts.

3.4. Contractor side in uncertainty of the client's preferences

We now take the view point of the construction company, who thinks that the client's preferences can be of three types: moderate, concerned about price, and concerned about aesthetics. These types of preference imply different values of the weights in Equation (8), shown in **Table 7**.

Table 7. Weights according to client type.

Client type	k_1	k_2	k_3
Moderate	0.2	0.5	0.3
Price concerned	0.2	0.1	0.7
Aesthetics concerned	0.2	0.7	0.1

For each set of values, the boundary of extreme efficient contracts (**Figure 9**) and the most equitable contracts (**Table 8**) are identified. The most equitable contract for the price-concerned client is #52 and for the aesthetic-concerned client is #55.

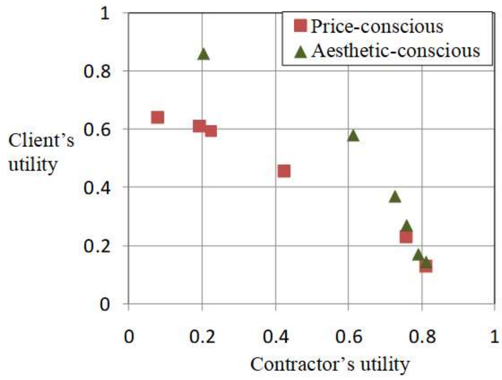


Figure 9. Extreme efficient frontier by client type.

Table 8. Equitable contracts according to client type.

Client type	#	Shape	Material	Time (months)	Price	Contractor's profit
Moderate	55'	Skirt	Concrete	4	$67,500	$38,350
	58'	Skirt	Aluminum	4	$80,000	$35,195
Price-concerned	52	Rectangle	Wood	4	$50,000	$31,800
Aesthetics-concerned	55	Skirt	Concrete	4	$75,000	$45,850

Contract #52 was not equitable to the client with moderate preferences (**Table 5**), and in that case, contract #55 had to be modified to #55' by changing the price from $75,000 to $65,000. Logically, the construction company's profit when dealing with a price-concerned client is lower than when negotiating with an aesthetic-concerned client.

If the construction company has probabilities about the type of client it is dealing with, the uncertainty tree of **Figure 10** can be constructed.

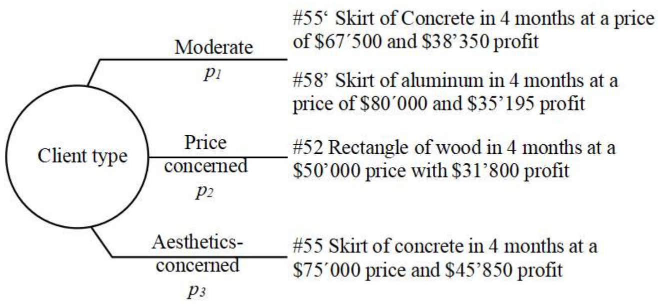


Figure 10. Probability tree for the client type.

The contractor can use this information in the following ways:

a) If the construction company has another job offer with a profit greater than the expected value of the profit in **Figure 10**, it can aggressively pursue a contract with a higher profit.

b) The construction company must open the negotiation with a contract with a high profit (for example #80 in **Table 7**), foreseeing to approach, as the negotiation proceeds, to more equitable contracts. In this sense, two situations can arise.

- The contractor may be confident in the type of client he is dealing with (one of p_1, p_2, or p_3 nears one). In this case, the contracts should tend to the equitable contract of the respective type of client, and no contract less favorable to the contractor should be accepted.

- The contractor is uncertain on the type of client across the table (p_1, p_2, and p_3 are comparable). In this case, he will try to steer the negotiations to the contract that is most beneficial to him (in the example, the equitable contract for an aesthetics-concerned client), being able to sequentially cede to the other equitable contracts less favorable to him.

4. Conclusions

This work has presented a methodology for analyzing the negotiation of construction companies and clients, taking a values-focused thinking perspective. The identification, structuring, and quantification of the objectives of the sides make it possible to find the most equitable contracts. The methodology is illustrated by a worked example related to the manufacture of a church dome. It is seen that for the contractor, the modelling effort concentrates on relating the different project elements to the cost, while for the client, more time should be devoted to eliciting his subjective preferences for the project characteristics. Additionally, taking the side of the contractor, it is shown that an effort to understand the probable objectives of the client can help the negotiation process, adjusting the designs and prices according to the perceived client preferences.

Author contributions: Conceptualization, MLCH and LVR; methodology, MLCH; formal analysis, MLCH; investigation, RGGT; writing—original draft preparation, MLCH; writing—review and editing, LVR and RGGT. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Keeney RL. Value-Focused Thinking. Harvard University Press; 1992.
2. Verheij H, Augenbroe G. Collaborative planning of AEC projects and partnerships. Automation in Construction. 2006; 15(4): 428-437. doi: 10.1016/j.autcon.2005.06.011
3. Murtoaro J, Kujala J. Project negotiation analysis. International Journal of Project Management. 2007; 25(7): 722-733. doi: 10.1016/j.ijproman.2007.03.002
4. Branconi CV, Loch CH. Contracting for major projects: eight business levers for top management. International Journal of Project Management. 2004; 22(1): 119-130. doi: 10.1016/S0263-7863(03)00014-0
5. Koskinen KU, Mäkinen S. Role of boundary objects in negotiations of project contracts. International Journal of Project Management. 2009; 27(1): 31-38. doi: 10.1016/j.ijproman.2007.10.006
6. Oliveira RAF, Lopes J, Abreu MI. Insights from a project procurement strategy through an action research. Procedia Computer Science. 2021; 181: 1002-1010. doi: 10.1016/j.procs.2021.01.275
7. Lippman SA, McCardle KF, Tang CS. Using Nash bargaining to design project management contracts under cost uncertainty. International Journal of Production Economics. 2013; 145(1): 199-207. doi: 10.1016/j.ijpe.2013.04.036
8. Tosselli L, Bogado V, Martínez E. A repeated-negotiation game approach to distributed (re)scheduling of multiple projects using decoupled learning. Simulation Modelling Practice and Theory. 2020; 98: 101980. doi: 10.1016/j.simpat.2019.101980
9. Ng ST, Li W. A parallel bargaining protocol for automated sourcing of construction suppliers. Automation in Construction. 2006; 15(3): 365-373. doi: 10.1016/j.autcon.2005.07.004
10. Shang T, Zhang K, Liu P, et al. What to allocate and how to allocate?—Benefit allocation in Shared Savings Energy

Performance Contracting Projects. Energy. 2015; 91: 60-71. doi: 10.1016/j.energy.2015.08.020
11. Tang Y, Chen Y, Hua Y, et al. Impacts of risk allocation on conflict negotiation costs in construction projects: Does managerial control matter? International Journal of Project Management. 2020; 38(3): 188-199. doi: 10.1016/j.ijproman.2020.03.002
12. Kang CC, Feng CM, Kuo CY. A royalty negotiation model for BOT (build-operate-transfer) projects: The operational revenue-based model. Mathematical and Computer Modelling. 2011; 54(9-10): 2338-2347. doi: 10.1016/j.mcm.2011.05.042
13. Zhang X, Bao H, Wang H, et al. A model for determining the optimal project life span and concession period of BOT projects. International Journal of Project Management. 2016; 34(3): 523-532. doi: 10.1016/j.ijproman.2016.01.005
14. Bao H, Peng Y, Ablanedo-Rosas JH, et al. An alternative incomplete information bargaining model for identifying the reasonable concession period of a BOT project. International Journal of Project Management. 2015; 33(5): 1151-1159. doi: 10.1016/j.ijproman.2014.12.004
15. Song J, Jin L, Zhao Y, et al. Using bargaining-game model to negotiate compensation for the early termination of BOT highway projects. Transportation Research Part A: Policy and Practice. 2017; 105: 197-209. doi: 10.1016/j.tra.2017.06.017
16. Chen YM, Wang SC. An evolutionary compensatory negotiation model for distributed dynamic scheduling. Applied Soft Computing. 2008; 8(2): 1093-1104. doi: 10.1016/j.asoc.2007.05.018
17. Badenfelt U. Fixing the contract after the contract is fixed: A study of incomplete contracts in IT and construction projects. International Journal of Project Management. 2011; 29(5): 568-576. doi: 10.1016/j.ijproman.2010.04.003
18. Miranda-Sarmento J, Renneboog L. Renegotiating public-private partnerships. Journal of Multinational Financial Management. 2021; 59: 100661. doi: 10.1016/j.mulfin.2020.100661
19. Kumar R, Rangan US, Rufín C. Negotiating complexity and legitimacy in independent power project development. Journal of World Business. 2005; 40(3): 302-320. doi: 10.1016/j.jwb.2005.05.006
20. Stapper EW. Contracting with citizens: How residents in Hamburg and New York negotiated development agreements. Land Use Policy. 2021; 111: 105743. doi: 10.1016/j.landusepol.2021.105743
21. Adebayo E, Werker E. How much are benefit-sharing agreements worth to communities affected by mining? Resources Policy. 2021; 71: 101970. doi: 10.1016/j.resourpol.2020.101970
22. Jalbert K, Dickinson KL, Baka J, et al. Influence in the right-of-way: Assessing landowners' risk decision-making in negotiating oil and gas pipeline easements. The Extractive Industries and Society. 2023; 14: 101276. doi: 10.1016/j.exis.2023.101276
23. Clemen RT. Making Hard Decisions: An Introduction to Decision Analysis. Duxury Press; 1996.
24. Hammond JS, Keeney RL, Raiffa H. Smart Choices. Harvard Business School Press; 1999.
25. Edwards W, Miles RF, von Winterfeldt D. Advances in Decision Analysis. Cambridge University Press; 2007.
26. Raiffa H. Negotiation Analysis: The Science and Art of Collaborative Decision Making. Harvard University Press; 2007.

Building Engineering 2024, 2(2), 1503.
https://doi.org/10.59400/be.v2i2.1503

Review

Bibliometric analysis of internet of things (IoT) in the construction industry using Scopus database: Trends, characteristics, and future directions

Sameer Jain

NICMAR University, Pune 411045, India; samejain1983@gmail.com

CITATION

Jain S. Bibliometric analysis of internet of things (IoT) in the construction industry using Scopus database: Trends, characteristics, and future directions. Building Engineering. 2024; 2(2): 1503. https://doi.org/10.59400/be.v2i2.1503

ARTICLE INFO

Received: 3 July 2024
Accepted: 20 August 2024
Available online: 7 September 2024

Abstract: This research examines the Internet of Things (IoT), a fast-developing technology that has transformed several industries, through bibliometric analysis of the building and construction sector. The current state of research, its features, and possible future paths are evaluated using the Scopus database. A thorough search of the literature conducted with Scopus produced a total of 2070 publications published between 2004 and 2022. Over the past five years, the number of IoT articles in the construction industry has significantly increased, according to the research. The study found that the top five countries for publications on this issue were China, Hong Kong, India, Portugal, and Sweden. The data suggests that a number of topics, such as energy management, construction automation, and smart buildings, have attracted a lot of attention. Additionally, the survey found that wireless networks and sensors were the IoT technology most frequently employed in the construction sector. The paper also makes recommendations for potential research directions, including the employment of cutting-edge technologies like blockchain and artificial intelligence, as well as the application of IoT in the building sector. The study's results shed light on market trends, unmet needs in the field, and prospective directions for Internet of Things applications in the construction sector.

Keywords: future directions; construction industry; Scopus database; sensors; wireless networks

1. Introduction

A network of physical objects that are networked and outfitted with sensors, software, and connections to gather and exchange data is referred to as the "Internet of Things" (IoT). Adoption of IoT technology has the potential to totally alter the construction sector by providing automated control, remote management, and real-time monitoring of construction processes and systems. A number of scholars have provided definitions of IoT from a review standpoint. The Internet of Things (IoT), according to researchers [1], is a "global infrastructure for the information society" that links virtual and real objects with communication and information technologies that are interoperable to allow improved services. However, researchers [2] define the Internet of Things (IoT) as the network of individually identifiable embedded computer devices within the existing internet infrastructure. Gubbi et al. [3] define the Internet of Things (IoT) as "a network of networks where each object or thing is uniquely identifiable and seamlessly integrated into the internet infrastructure."

IoT technology could potentially be applied by the construction industry in a number of ways, such as building design, construction management, building operation, and building maintenance, according to Hammad et al. [4]. IoT-enabled sensors have the potential to lower building energy consumption, verify the structural integrity of structures, and facilitate equipment and building supply tracking. IoT-based systems for monitoring concrete temperature and humidity during curing [5] and concrete deformation and stress during curing [6] are only two examples of the particular IoT applications in construction that have been the subject of other research. In order to increase the quality and efficiency of construction, Wang et al. [7] suggested a framework that blends building information modeling (BIM) with the Internet of Things.

Furthermore, sensors and wearable technologies are being used more often to collect real-time data on worker position, temperature, humidity, noise levels, and vibration on construction sites [8]. Sensible resource allocation, enhanced operational efficiency, and worker safety monitoring can all be made possible by this data. On a construction site, wearable technology—like smart helmets—can be used to track worker position and activity and measure vital indications like body temperature and heart rate. Similar to this, sensors placed across a construction site may gather information on variables like temperature, humidity, and noise levels to enhance working conditions and lower the chance of mishaps. While deploying sensors and wearable technology can increase worker safety, reduce expenses, and enhance operational performance, there are certain drawbacks, such as resolving privacy issues associated with wearable technology use and ensuring the accuracy and dependability of the data collected.

2. Research GAP analysis

The following is a potential gap analysis for Internet of Things (IoT) major and minor studies in the construction sector or on construction sites:

- Lack of standardization: The Internet of Things (IoT) offers great promise for the construction sector, but data interchange and interoperability across different IoT systems and devices are hampered by the lack of standards for communication protocols, hardware, and software [9,10].
- Limited integration with BIM: The construction sector uses BIM extensively for activities like designing, planning, and managing building projects, but there is still a long way to go before BIM and IoT are fully integrated. To enhance building procedures and results, further study is needed on how to merge the two technologies [11,12].
- Cybersecurity risks: With the proliferation of IoT devices and systems in the construction industry, there is a greater risk of cybersecurity threats and assaults. Further research is required to secure IoT-enabled construction sites and protect sensitive data and information [1,13].
- Limited attention to user experience: Although IoT systems and devices have the potential to enhance construction processes and results, their complexity, lack of user-friendliness, and low usability may prevent professionals and workers from adopting and accepting them. Thus, further study is required to design and build IoT systems that are user-friendly, intuitive, and responsive to their requirements and preferences [11,14].
- Inadequate consideration of social and organizational factors: While the majority

of research on IoT in the construction sector has concentrated on the technical aspects of the technology, more study is required to understand the social and organizational factors—such as organizational culture, change management, and stakeholder engagement—that may influence its adoption and implementation [12,14].

Based on the current literature, some possible research gaps in the field of internet of things in the construction industry or construction site are:

- IoT and BIM integration: Using IoT and Building Information Modeling (BIM) together to enable real-time decision-making and monitoring in building projects [1,7,15].
- Standardized IoT platforms: The creation of uniform and compatible Internet of Things platforms to provide easy data sharing and cooperation amongst construction project participants [14,16].
- Sensor placement and data collection: Sensitivity placement and data gathering methods optimization for precise and dependable building site parameter (e.g., temperature, humidity, noise, vibration) measurement [17,18].
- Security and privacy: A look at the security and privacy issues surrounding the usage of IoT data and devices in building projects [19].
- Barriers to adoption: Determining the primary barriers to the adoption and use of IoT technologies in the construction sector and creating plans to get around them [1,20].

3. Research methods

Bibliometrics is a quantitative research tool used to analyze and assess the worth of scientific study in a certain topic. Many bibliometric approaches are available to examine trends in publication, citation, and other bibliographic data. Commonly used methods include scientometrics, bibliographic coupling, co-citation analysis, and citation analysis. Citation analysis leverages citations within a collection of papers to identify influential authors, organizations, and publications, while co-citation analysis examines the frequency with which two publications are mentioned together [21,22]. Scientometrics studies the organization of knowledge and discourse patterns within the literature of a scientific field, while bibliographic coupling utilizes shared source analysis to map a field's intellectual structure [23,24]. These techniques have been widely applied across various academic fields, such as engineering, social sciences, and economics, to gain insights into research trends and academic impact [25,26].

3.1. Data source and search strategy

A popular resource for performing bibliometric analysis is the Scopus database. The following search approach can be used to look for articles on the Internet of Things (IoT) in the construction industry:

- Access the Scopus database through the institutional library portal.
- Click on the "Advanced Search" option.
- Enter the following search terms in the search fields:
    - TITLE-ABS-KEY ("Internet of Things" OR IoT) AND TITLE-ABS-KEY

(construction OR building).

- Set the date range to “2000–2022” to capture all relevant publications.
- Limit the search to academic journals, conference proceedings, and book chapters.
- Export the search results in CSV or Excel format for further analysis [27].

In March 2023, a search was conducted in the Scopus database to gather data on the “Internet of Things in the construction industry.” Review articles published between 2004 and 2023 were the primary focus. The search strategy employed keywords such as “Internet of Things,” “IoT,” and “construction,” yielding 2070 documents after excluding irrelevant articles. This approach provided comprehensive coverage of the field from 2004 to 2023, allowing for in-depth bibliometric analysis [28,29].

TITLE-ABS-KEY ((“Internet of things” OR “IOT “OR “IoT”) AND “Construction”) AND PUBYEAR > 2004 AND PUBYEAR < 2023 AND (LIMIT-TO (DOCTYPE, “ar”)). This query string’s output was 2070 documents.

This search strategy retrieves publications that include the search terms in their title, abstract, or keywords. The date range can be adjusted to focus on more recent publications or to capture a longer historical period. Additionally, the search terms can be refined or expanded based on the research question and the focus of the analysis.

Steps involved in the flow chart for the collection of Internet of Things (IoT) in construction industry publications from the Scopus index (**Figure 1**):

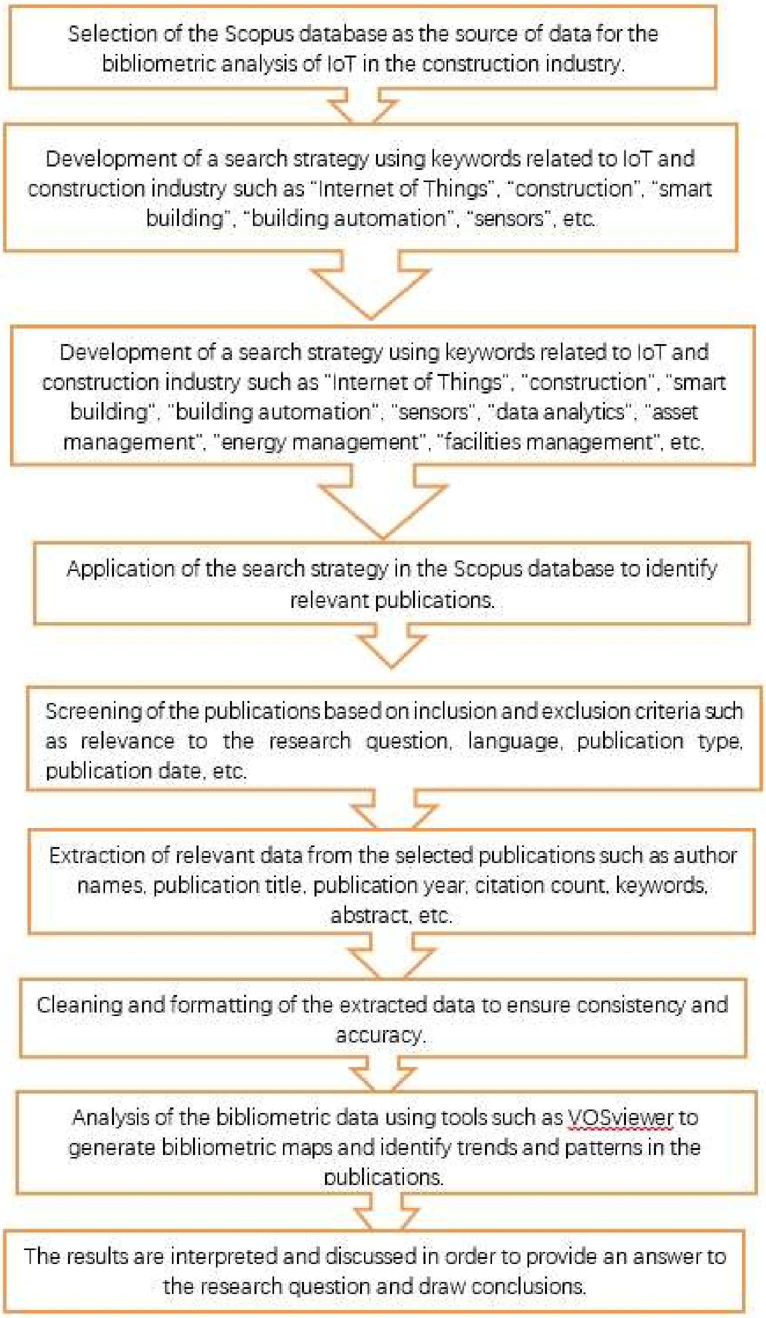


Figure 1. Methodology for doing the bibliometric analysis.

3.2. The bibliometric maps

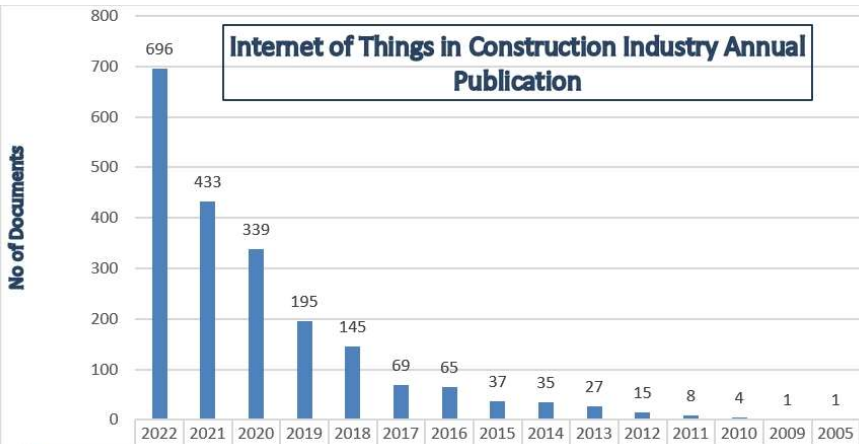
To visually represent the connections between various authors, research topics, and academic domains, bibliometric maps may be made using specialized software like VOSviewer. The articles that are often mentioned together are identified by co-citation analysis, and VOSviewer shows clusters of these articles along with the connections between them. These maps can help find possible partners, provide crucial information about the organizational structure of various research topics, and direct funding decisions. Scholars can also find important research topics and understudied regions that need more investigation with the use of bibliometric maps using the scopus database [30–32].

Bibliometric maps have been created with VOSviewer by several investigations in diverse fields. Zhang et al. [33] employed VOSviewer to illustrate the connections across various research domains and underscore significant research subjects throughout their examination of the literature on climate change adaptation. Similar to this, Zupic et al. [34] utilized VOSviewer to determine the most significant authors and research themes in a review of the literature on digital transformation. Bibliometric maps made using VOSviewer may be a useful tool for properly seeing and comprehending the organization of research topics. These maps can also be a helpful tool for guiding collaborations and future lines of inquiry.

4. The results and discussion

4.1. Research interest in publication output and growth

There were 2070 research articles published on the subject of the Internet of Things in the construction industry between 2005 and 2022. A significant increase in interest that began in 2018 and persisted until 2022, when the number of publications doubled annually, caused a steady increase in the number of publications. This trend is anticipated to increase going forward. A fee is usually required to access the majority of these articles. This field is extremely interdisciplinary and is being studied by numerous research groups across the globe. Engineering was the primary subject of the articles (1189), which were also heavily focused on computer science (1146), mathematics (247), materials science (220), physics and astronomy (201), energy (187), social sciences (147), environmental science (133), and business management and accounting (113). This demonstrates how the social sciences are just one aspect of the Internet of Things' highly interdisciplinary nature in the construction industry. The research's articles were written in ten different languages (**Figures 2–7**).



	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2005
Documents	696	433	339	195	145	69	65	37	35	27	15	8	4	1	1

Figure 2. The annual and total number of research articles on the Internet of Things in the construction industry published in Scopus between 2004 and 2022.

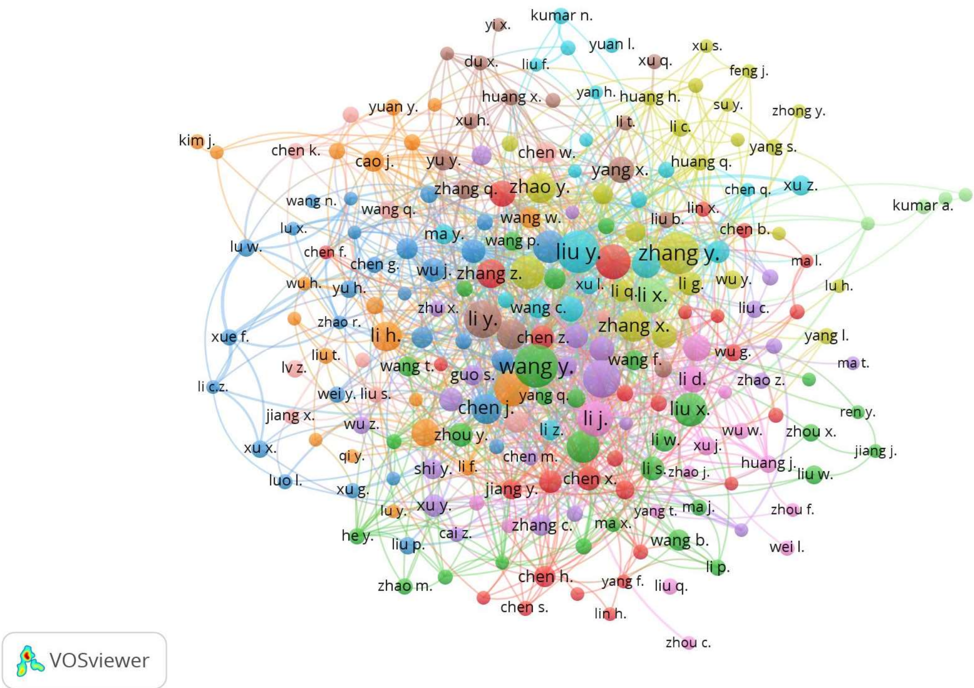


Figure 3. A graphic representation of a bibliometric map produced using network visualization that demonstrates author co-authorship links.

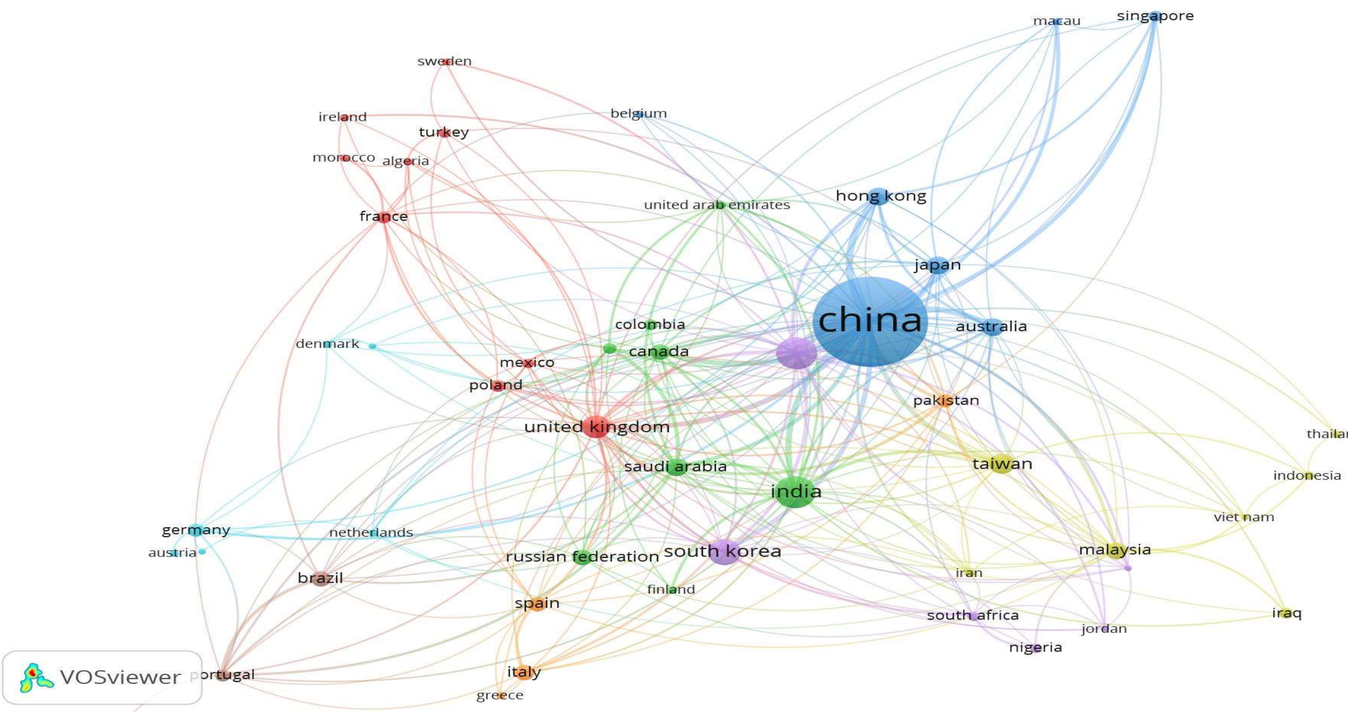


Figure 4. A snapshot of the network-based bibliometric map created using co-authorship data from various nations.

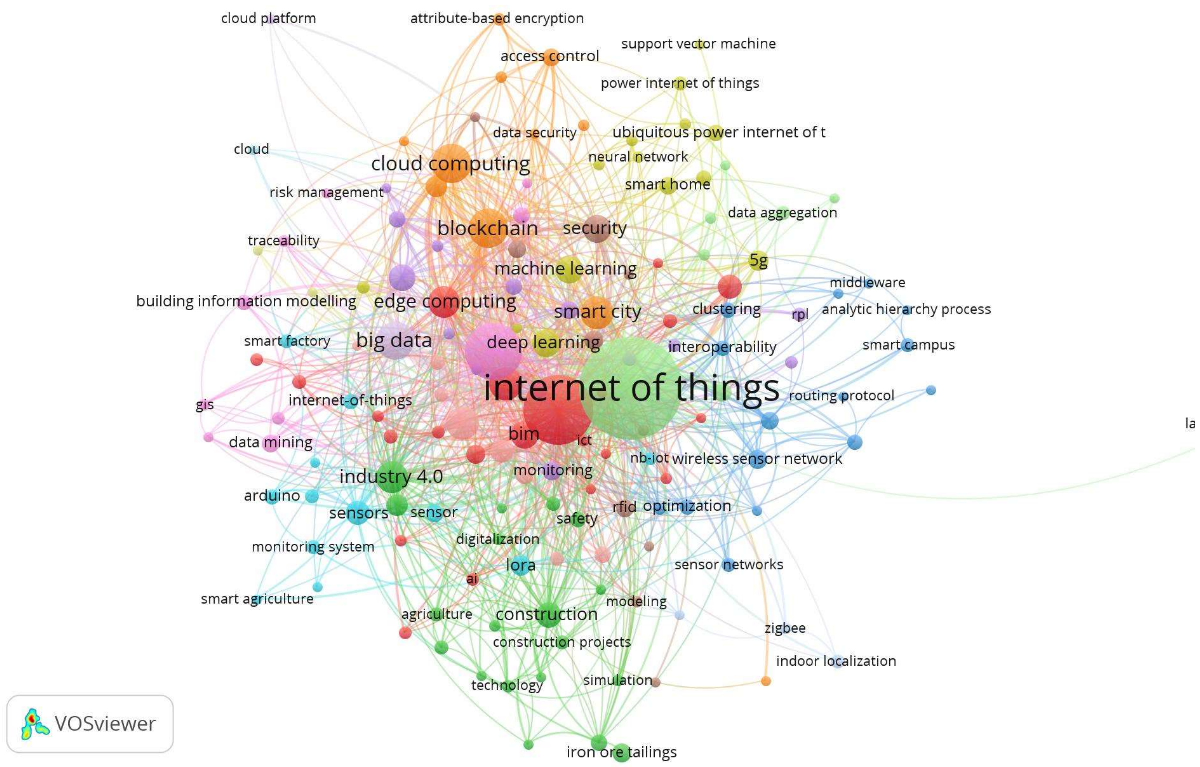


Figure 5. An examination of the co-occurring author keywords produced a bibliometric map that is represented visually here. In a specific subject of study, the map aids in locating the most popular and connected keywords.

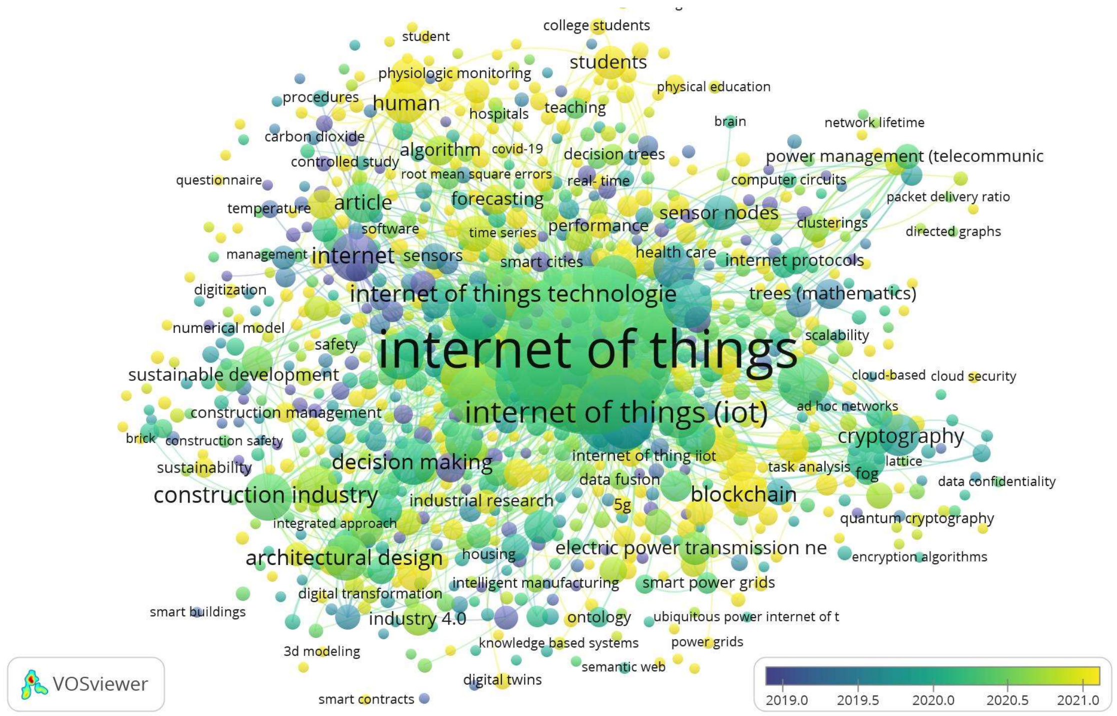


Figure 6. This is a snapshot of the bibliometric map generated through author keyword co-occurrence analysis, using the overlay visualization mode. The map displays the relationships between keywords based on their co-occurrence in publications. To be included in the map, a keyword must occur at least five times in the analyzed literature.

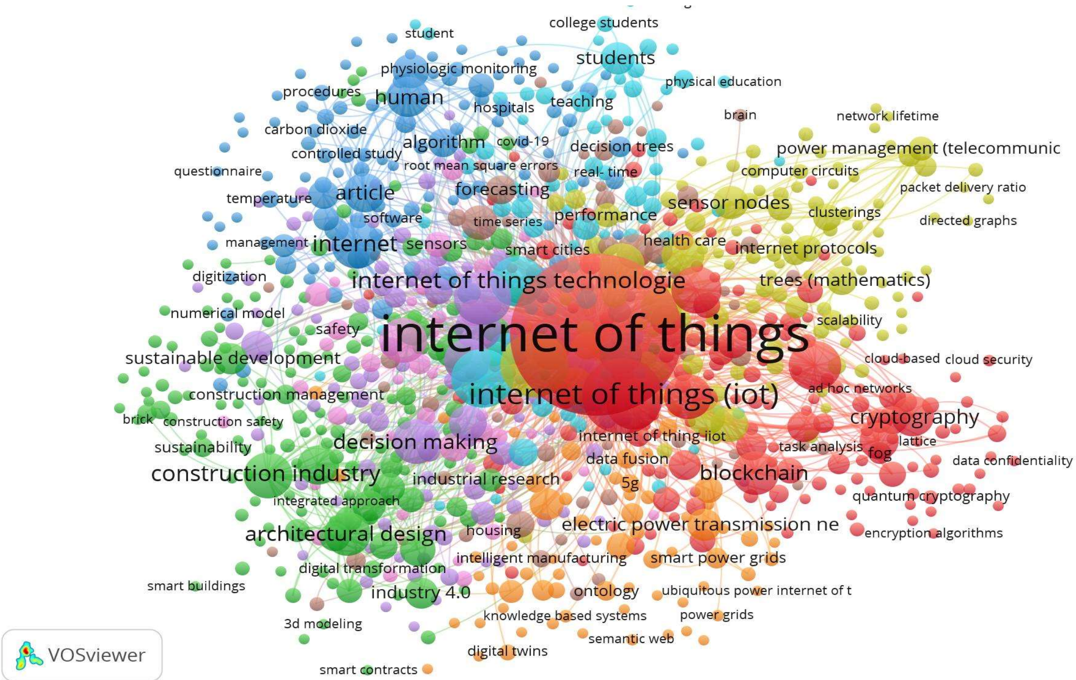


Figure 7. A snapshot of the bibliometric map generated through the analysis of all keywords' co-occurrence.

4.2. Leading authors

The 10 most prolific journals conducting research on the Internet of Things (IoT) in the construction industry are listed in **Table 1**. These journals are ranked based on the number of times their papers have been cited, with notable contributions from IEEE Access, IEEE Internet of Things Journal, and Wireless Communications and Mobile Computing. The most cited article from each journal is also highlighted, showcasing the breadth of research in this field.

Table 2 lists the 15 authors with the most publications related to IoT in construction research. The authors represent a range of countries, including China, Hong Kong, India, Portugal, Sweden, the United Arab Emirates, Nigeria, and the United States. The first works of these authors date from 1989 to 2020, with various positions held by the authors such as first author, co-author, and last author, which often denotes seniority or a supervisory role. Guizani, Mohsen, with 1,285 articles and an h-index of 82, leads the list, followed by Rodrigues, Joel J.P.C., and Kumar, N. It should be noted that the authors mentioned in **Table 2** may differ from those associated with the most cited papers in **Table 1**.

Table 1. The top 10 journals that have conducted the most research on the Internet of Things (IoT) in the construction industry are listed in the list below. The most cited article for each journal is listed, and these journals are ranked according to how many times their papers have been cited.

Journal	TP	TC	CiteScore 2022	The most cited article(reference)	Times cited	Publisher
IEEE Access	54,382	479,740	8.8	A Metaverse: Taxonomy, Components, Applications, and Open Challenges	160	IEEE
IEEE Internet of Things Journal	5079	86,450	17	Secure Artificial Intelligence of Things for Implicit Group Recommendations	106	IEEE
Wireless Communications and Mobile Computing	4309	9338	2.2	Deep Reinforcement Learning-Based Path Control and Optimization for Unmanned Ships	48	HINDAWI
Mobile Information Systems	2594	3406	1.3	Ambient Assistive Living for Monitoring the Physical Activity of Diabetic Adults through Body Area Networks	17	HINDAWI
Sensors Switzerland	30,875	206,342	6.7	Comparing YOLOv3, YOLOv4 and YOLOv5 for Autonomous Landing Spot Detection in Faulty UAVs	104	Multidisciplinary Digital Publishing Institute (MDPI)
Computational Intelligence and Neuroscience	4168	7660	1.8	Applying Dynamic Systems to Social Media by Using Controlling Stability	37	HINDAWI
Automation in Construction	1657	27,221	16.4	Pavement distress detection using convolutional neural networks with images captured via UAV	48	ELSEVIER
Sustainability Switzerland	48,515	276,102	5.7	The Impact of Financial Development and FDI on Renewable Energy in the UAE: A Path towards Sustainable Development	67	Multidisciplinary Digital Publishing Institute (MDPI)
Sensors	30,875	206,342	6.7	Comparing YOLOv3, YOLOv4 and YOLOv5 for Autonomous Landing Spot Detection in Faulty UAVs	104	Multidisciplinary Digital Publishing Institute (MDPI)
Security and Communication Networks	2492	6248	2.5	Computational Technique Based on Machine Learning and Image Processing for Medical Image Analysis of Breast Cancer Diagnosis	18	HINDAWI

TP: Total Publications; TC: Total Citation.

Table 2. The 15 authors with the most publications in the subject of Internet of Things in Construction research are listed below.

Sr No.	Author	Scopus Author ID	Year of 1st Publication*	TP	h-index	TC	Current affiliation	Country
1	Rodrigues, Joel J. P. C.	25930566300	2002**	1114	79	20,307	Instituto de Telecomunicacoes, Lisboa	Portugal
2	Xue, Fan	56720069500	2006***	85	28	1862	The University of Hong Kong, Pokfulam	Hong Kong
3	Lu, Weisheng Wilson	24173836000	2003***	238	49	5104	The University of Hong Kong, Pokfulam	Hong Kong
4	Lv, Zhihan	55925162500	2011*	437	60	7880	Uppsala Universitet, Uppsala	Sweden
5	Kumar, N.	57206866080	1994***	896	88	17,507	Shri Ramswaroop Memorial University, Barabanki	India
6	Liu, Zhansheng	57191688199	2010***	76	11	328	Beijing University of Technology, Beijing	China
7	Gehlot, Anita	57709976000	2015*	205	12	636	Uttaranchal University, Dehradun	India
8	Guizani, Mohsen	7004750176	1989**	1285	82	31,645	Mohamed Bin Zayed University of Artificial Intelligence, Abu Dhabi	United Arab Emirates
9	Li, Clyde Zhengdao	57188592789	2014*	51	27	2136	Shenzhen University, Shenzhen	China
10	Li, Heng	8692514900	1992***	605	75	14,519	Hong Kong Polytechnic University, Kowloon	Hong Kong
11	Singh, Rajesh	57610169600	2002***	238	13	836	Uttaranchal University, Dehradun	India
12	Zhang, Mingwu	22636534500	1993**	227	23	1585	Hubei University of Technology, Wuhan	China
13	Zhang, Yang	35346173600	2005*	90	11	371	Beijing University of Posts and Telecommunications, Beijing	China
14	Arowoiya, Victor Adetunji	57215611010	2020*	10	5	57	Federal University of Technology, Akure	Nigeria
15	Du, Xiaojiang	8371278000	2002*	623	59	11,082	Stevens Institute of Technology, Hoboken	United States

*First Author, ** Co- Author, ***Last Author.

4.3. Author keywords

The authors used co-authorship, co-occurrence with countries, and all keywords as units of analysis with the full counting method to identify significant authors, countries, and keywords in the field of Internet of Things in construction. For co-authorship with authors, they applied certain thresholds, such as a maximum of 25 authors per document and a minimum of 5 documents for an author, and 221 authors met these criteria. They calculated the total strength of the co-authorship links for each of these 221 authors and selected the ones with the highest link strength. This resulted in the creation of 11 clusters, each containing a different number of items.

Similarly, for co-occurrence with countries, they set a maximum of 25 countries per document and a minimum of 5 documents for a country, and 50 countries met these criteria. They calculated the total strength of the co-authorship links for each of these 50 countries and selected the ones with the highest link strength.

The researchers selected a minimum threshold of five occurrences for each keyword in order to carry out a co-occurrence analysis of both author keywords and keyword co-occurrences. As a result, 152 author keywords and 919 related keywords for keywords were found. Then, only the keywords with the strongest connections were kept after the researchers evaluated the overall strength of each keyword's co-occurrence links. Ultimately, this process led to the formation of 10 clusters for all keywords and 152 keywords for author keywords.

4.4. Discussion

A) Integration of IoT with blockchain

The integration of blockchain technology with IoT can significantly enhance the construction industry by improving data security, transparency, and reliability. Here's how:

- Data integrity and security: Blockchain's decentralized ledger system can secure IoT data by providing an immutable record of all transactions. In construction, this means that data from IoT devices, such as sensor readings and equipment logs, can be recorded in a way that prevents tampering and fraud. This ensures that the data used for decision-making is accurate and trustworthy.
- Smart contracts: Blockchain can facilitate the use of smart contracts—self-executing contracts with the terms directly written into code. In construction projects, smart contracts can automate various processes, such as payments and compliance checks, based on data collected from IoT devices. For instance, a smart contract could automatically release payments to subcontractors once IoT sensors confirm that specific milestones are met.
- Enhanced traceability: Blockchain can provide a transparent and traceable record of all IoT-generated data, which is particularly valuable in managing complex construction projects with multiple stakeholders. This traceability can help in verifying the authenticity of materials, monitoring construction progress, and ensuring compliance with regulatory standards.

B) Integration of IoT with Artificial Intelligence (AI)

Integrating AI with IoT can further revolutionize the construction industry by enabling predictive analytics, automation, and enhanced decision-making.

- Predictive maintenance: AI algorithms can analyse data from IoT sensors to predict when equipment or infrastructure will need maintenance. This proactive approach can prevent costly breakdowns and extend the lifespan of machinery and materials. For example, AI can analyse vibration patterns from IoT sensors to predict potential failures in construction equipment.
- Automated construction processes: AI-powered systems can use IoT data to automate various construction processes. For instance, AI can control robotic systems for tasks such as bricklaying or concrete pouring based on real-time data from IoT sensors, improving efficiency and precision in construction.
- Improved decision-making: AI can analyze vast amounts of IoT data to provide actionable insights and recommendations for construction management. By processing data on building conditions, energy usage, and worker productivity, AI can help project managers make informed decisions, optimize resource allocation, and enhance overall project performance.
- Risk management: AI algorithms can assess risks by analysing data from IoT devices and historical records. For example, AI can predict potential safety hazards by analysing environmental conditions and worker behaviour data, enabling better risk management and enhancing site safety.

C) Combined impact of IoT, blockchain, and AI

The combined integration of IoT, blockchain, and AI can lead to several transformative impacts in the construction industry:

- Increased efficiency: The synergy between these technologies can streamline construction processes by automating routine tasks, optimizing resource use, and reducing manual errors. This leads to faster project completion times and lower costs.
- Enhanced data utilization: By integrating AI with IoT data recorded on a blockchain, construction firms can leverage rich, real-time insights to drive decision-making. This integrated approach allows for better forecasting, resource management, and overall project planning.
- Strengthened collaboration: Blockchain’s transparency combined with AI’s analytical capabilities can foster greater collaboration among stakeholders. All parties can access accurate, real-time information, leading to better coordination and reduced conflicts.
- Greater compliance and accountability: The integration ensures that all processes are documented, automated, and auditable, which strengthens compliance with industry standards and regulations. Blockchain’s immutable ledger and AI’s monitoring capabilities enhance accountability throughout the project lifecycle.

5. Challenges and future directions

While the integration of these technologies offers numerous benefits, there are challenges to address:

- Technical Complexity: Integrating blockchain and AI with IoT requires advanced technical expertise and infrastructure. Construction firms may face challenges in implementing and maintaining these systems.

- Data Privacy and Security: Ensuring data privacy and security is critical when combining these technologies. It is essential to address potential vulnerabilities and ensure compliance with data protection regulations.
- Cost and Scalability: The initial investment and ongoing costs associated with deploying and maintaining these technologies can be significant. Scalability considerations need to be addressed to ensure these solutions are cost-effective for different project sizes.

Future research should focus on developing scalable and cost-effective solutions for integrating IoT, blockchain, and AI, addressing technical and regulatory challenges, and exploring new applications and use cases in the construction industry.

6. Conclusion

The study analyzed the research trends, characteristics, and future directions of IoT in the construction industry through a bibliometric analysis of 2070 publications in the Scopus database from 2004 to 2022. The analysis revealed a rapid increase in publications on IoT in the construction industry, with China, India, the United States, and the United Kingdom being the leading countries in terms of publications. Smart buildings, building energy management, and construction automation were identified as the most researched topics, and sensors and wireless networks were the most frequently used technologies. The study suggested potential research directions for the future, such as the integration of AI and blockchain with IoT applications in the construction industry. Overall, the findings of the study provide insights into the current research trends, gaps, and future directions in IoT applications in the construction industry.

Conflict of interest: The author declares no conflict of interest.

References

1. Alshawi M, Aziz Z, Sutrisna M. Internet of things (IoT) in construction: A review of current status and future directions. Automation in Construction. 2018; 86: 224–241.
2. Atzori L, Iera A, Morabito G. The Internet of Things: A survey. Computer Networks. 2010; 54(15): 2787–2805. doi: 10.1016/j.comnet.2010.05.010
3. Gubbi J, Buyya R, Marusic S, et al. Internet of Things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems. 2013; 29(7): 1645-1660. doi: 10.1016/j.future.2013.01.010
4. Hammad A, Varghese K, Saeed M. The internet of things (IoT) applications in the construction industry. IEEE. 2018.
5. Hu L, He X, Wang X, Wang Z. An internet of things-based temperature and humidity control system for concrete curing. Advances in Civil Engineering. 2020.
6. Li B, Ma Q, Zhang L, Lin Q. Internet of things (IoT) system for concrete strain and stress monitoring during the curing process. Sensors. 2019; 19(13): 2969.
7. Wang J, Xu X, Wang X. Internet of things and building information modeling-based intelligent construction management system for prefabricated construction. Journal of Cleaner Production. 2019; 229: 1043–1055.
8. Yang S, Liu Y, Liu M, Wang Z. Sensing Technologies for Monitoring Construction Noise and Vibration: A Review. Journal of Computing in Civil Engineering. 2018; 32(5): 04018025.
9. Chen X, Lu W, Wu Q, Jiang X. Integration of Internet of Things and Building Information Modeling in construction industry: A review. Journal of Computing in Civil Engineering. 2020; 34(3): 04020002.
10. Wang D, Niu Y, Zhang T, Ma Y. A survey of the application of the Internet of Things in construction engineering. Applied

Sciences. 2019; 9(22): 4704.
11. Mokhtarian P, Abdollahzadeh G, Iranmanesh M. BIM and IoT: Integration challenges and opportunities. Automation in Construction. 2021; 122: 103463.
12. Cao M, Yu W, Wang X, et al. Research on the application of the Internet of Things in construction project management. Journal of Intelligent Fuzzy Systems. 2019; 37(3): 3485–3493.
13. Tao Y, Luo H, Chen X. Security challenges for Internet of Things in the construction industry: A review. Journal of Construction Engineering and Management. 2019; 145(1): 04018105.
14. Zhang X, Wang Y, Zeng Q, Deng X. IoT in construction: A review and a path forward. Automation in Construction. 2019; 100: 135–148.
15. Haas CT, Goncalves G, Gu N. Building information modeling and internet of things integration: A review. Automation in Construction. 2018; 93: 1-15.
16. Lu Y, Liao Y, Bai Y. An interoperable Internet of Things platform for construction management. Automation in Construction. 2020; 110: 103031.
17. Serrano D, Torres L, Gómez A, García Á. An overview of wireless sensor networks and the Internet of Things for monitoring and management of buildings. Sensors. 2017; 17(6): 1301.
18. Hasan MH, Demian P, Ghosh R. A review of sensor placement optimization techniques in construction engineering and management. Automation in Construction. 2019; 107: 102932
19. Xu X, Wu Q, Lin J, et al. Internet of Things in construction: A review of applications, data privacy, and security issues. Journal of Computing in Civil Engineering. 2020; 34(6): 04020042.
20. Wang X, Zhang J, Gao J. Barriers and strategies of implementing the Internet of Things in construction. Journal of Construction Engineering and Management. 2020; 146(2): 04019104.
21. Almarashdeh I, Bao Y, et al. Cybersecurity risks and protection for the Internet of Things in construction: A review. Automation in Construction. 2021; 127: 103750.
22. Borgia E. The Internet of Things vision: Key features, applications and open issues. Computer Communications. 2014; 54: 1–31. doi: 10.1016/j.comcom.2014.09.008
23. Cao X, Lin J, Zhou X, Zhang Y. Building information modeling meets Internet of Things: A review. Automation in Construction. 2020; 110: 103014.
24. De Moura Oliveira PB., Ferraz A. Mapping the scientific literature on the Internet of Things: A bibliometric analysis. Journal of Cleaner Production. 2019; 212: 1287–1306.
25. Garfield E. Citation indexing: Its theory and application in science, technology, and humanities. Wiley; 1979.
26. Glänzel W, Moed HF. Journal impact measures. In: Moed HF, Glänzel W, Schmoch U (editors). Handbook of Quantitative Science and Technology Research. Springer; 2019. pp. 473–507.
27. Katiyar A, Kumar P. A Review of Internet of Things (IoT) in Construction Industry: Building a Better Future. International Journal of Advanced Science Computing and Engineering. 2021; 3(2): 65-72. doi: 10.62527/ijasce.3.2.53
28. Karimi M, Zavadskas EK. Bibliometric analysis of construction innovation research: a scientometric review. Journal of Cleaner Production. 2021; 261: 121097.
29. Li Q, Chen Z, Liu L, et al. Smart Helmet-Based Real-Time Construction Worker Safety Monitoring System. Journal of Computing in Civil Engineering. 2021; 35(2): 04020024.
30. Noronha T, Goh YM. The IoT and its impact on the future of the construction industry. Procedia Engineering. 2019; 196: 1213–1220.
31. Small H. Co-citation in the scientific literature: A new measure of the relationship between two documents. Journal of the American Society for Information Science. 1973; 24(4): 265–269. doi: 10.1002/asi.4630240406
32. Scopus. Advanced search. Available online: https://www.scopus.com/search/form/advanced (accessed on 4 June 2024).
33. Zhang Y, Feng C, Li Z. Mapping the intellectual structure of climate change adaptation research: A co-citation analysis. Journal of Cleaner Production. 2019; 229: 1285–1295.
34. Zupic I, Novak I, Kveder D. O. Digital transformation research: A bibliometric review and bibliometric map analysis. Sustainability. 2020; 12(21): 8914.

Building Engineering 2024, 2(2), 1314.
https://doi.org/10.59400/be.v2i2.1314

Review

Building materials alternative approaches: A bibliometric and review approach

Nathalie Tornay

LRA—Laboratoire de Recherche en Architecture, ENSA—École Nationale Supérieure d'Architecture de Toulouse, Université de Toulouse, 31106 Toulouse, France; nathalie.tornay@toulouse.archi.fr

CITATION

Tornay N. Building materials alternative approaches: A bibliometric and review approach. Building Engineering. 2024; 2(2): 1314.
https://doi.org/10.59400/be.v2i2.1314

ARTICLE INFO

Received: 22 April 2024
Accepted: 9 July 2024
Available online: 29 July 2024

Abstract: In this paper, we develop a global vision of environmental impact with alternative building materials in architectural design. A bibliometric study is based on 1827 scientific research publications on alternative materials produced between 1998 and 2022. More than 90% of these documents have been published in the last ten years. This bibliometric study goal is to develop a systemic approach for the characterisation of alternative solutions in the context of scarce resource context and climate change. This study highlights three different approaches: 1) an 'integrative' approach that develops an implementation approach combining environmental concerns and design teams' own working methods in the selection of materials; 2) an 'additive' approach that selects some environmental criteria (carbon footprint and energy consumption) in addition to implementation issues; 3) a 'subtractive' approach that focuses solely on implementation issues.

Keywords: building material; alternative material; environmental impact; systemic; bibliometry

1. Introduction

Increasing awareness of resource scarcity [1–3] and carbon footprints [4–6] has strongly impacted the building material choice. Several ways have been explored on ecological and environmental consequences of raw material selection, manufacturing processes, and waste management. The life cycle assessment methods have made it possible to specifically look at ecological and environmental building material impacts. In this context, the idea of using alternative building materials has emerged. Disparate definitions appearing in multiple references:

This approach aims at finding complementary materials with low GHG emissions in order to manufacture such building products as cement or concrete [7]. The definition of what a "conventional" material is depends to a great extent on the parameters. The daily professional practice, nevertheless, demands no special explanation on the issue of defining "conventional materials", since it is taken for granted. In a systematic way, the construction of small-to-medium-sized buildings for residential use is developed with a reinforced concrete structure, vitrified ceramic wallings, polyurethane or polystyrene foam insulation, aluminum or PVC window and door frames, ceramic floor finishing and parquet floors, chemical paintings, and interior wood treatment in PVC. (…) Other possibilities in the structure or load-bearing walls, such as wood, or the use of other materials naturally found, e.g., wood, cork, etc., have almost disappeared from the conventional construction and can only be found in very special cases [8] or Alternative building materials are increasingly being employed to replace the conventional and traditional building materials. In some parts, though not widely common, earth-based materials are modified with plant residues or animal dung to improve the durability and the architectural aesthetics [9].

In the absence of a comprehensive study on alternative materials, countless isolated experiments have featured in scientific publications. Today, syntheses are beginning to compile and analyse research work focusing on a material type, such as cement to remedy the impact of clinker manufacturing [10–12], concrete to question the substitution of raw material by agricultural or industrial waste [13–15], brick to question the carbon impact of baking during the terracotta manufacturing process or to study the location of raw material for raw earth construction [16], wood to compare the impacts of CLT manufacturing [17,18], or phase change materials to analyse energy gains [19,20], etc. These studies concern all types of construction systems (wall, floor, roof) with bearing [21,22], insulating [23,24] and protective materials [25,26]. They look at the architectural scale [27,28] to improve the environmental evaluation of buildings, or even the urban scale [29,30] with the challenges of the urban climate. Some of this research is part of a strong local implementation to develop an approach towards circular construction (economy, local resources, etc.).

Each of these works reveals a fragmented vision of the concept of alternative materials, without ever contextualising it on a more comprehensive scale.

The purpose of this article is to compile a large number of research publications on alternative materials in an attempt to develop a systemic approach. Faced with the disparity of situations and experiences, it is necessary to take into account the various interactions existing between them and their complexities to be able to identify alternative material characteristics, including their links to environmental issues and areas of construction.

To this end, the working method is oriented towards creating a corpus from scientific publications on alternative building materials and analysing it with bibliometric tools. Bibliometry is defined as the application of mathematics and statistical methods to books, articles, and other means of communication [31]. Here it is used in the form of mapping to visualise and interpret the networks of metadata relationships taken from the publications studied.

A bibliometric network consists of nodes and edges. The nodes may be for instance publications, journals, researchers, or keywords. The edges indicate relations between pairs of nodes. (…) Bibliometric networks are usually weighted networks. Hence, edges indicate not only whether there is a relation between two nodes or not but also the strength of the relation [32].

This work is in keeping with the bibliometric reviews of sustainable construction research [33] or the Building Information Modelling (BIM) [34,35].

2. Working method

This section describes the procedures used to identify research related to alternative building materials as well as the methods used to analysis the corpus from the scientific literature.

2.1. Corpus creation

A corpus has been compiled from documents extracted from the Science Direct database. This is Elsevier's main platform, containing peer-reviewed scientific papers with journal articles, books, book chapters, and conference articles. No start date has been specified, so that the oldest articles in the literature can be identified.

The search string 'building material' and 'alternative' has been entered in the search engine. The Science Direct platform identified 1998 documents. After analysing the summaries, some were excluded as they were not relevant to the theme. Once sorted, the final corpus includes 1827 publications on alternative building materials.

The following diagram shows the annual distribution of the number of publications since 1998, the date of the first listed publications in scientific fields, even if this topic is not new (1923) [36]. Between 1998 and 2001, this topic was rarely dealt with in scientific literature, as demonstrated in **Figure 1**, and it was really in the last ten years that the subject was developed (90% of the documents in the selected corpus).

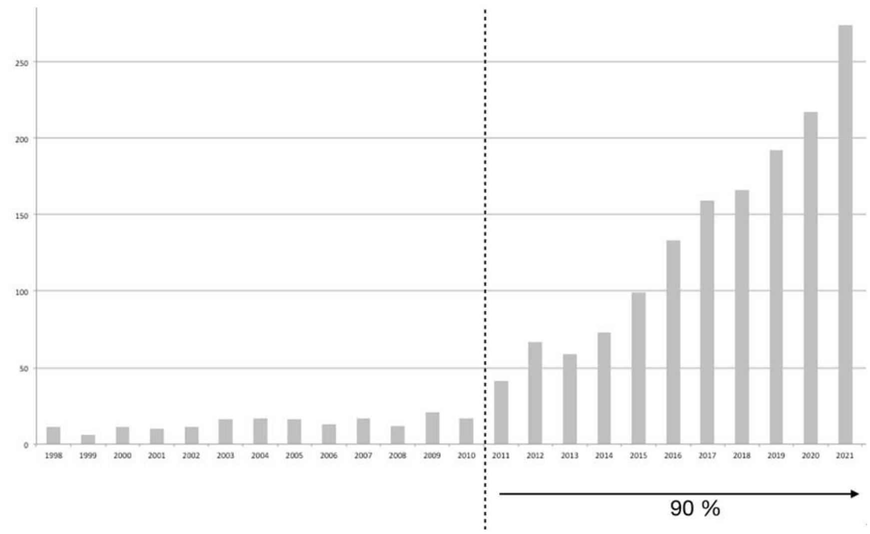


Figure 1. Annual distribution of the number of publications since 1998.

The corpus consists mainly of scientific articles (93%) and book chapters (7%), it counts 6677 authors of which less than 1% total a dozen different publications.

2.2. Corpus analysis

The corpus of 1827 documents contains bibliographic information, which is indexed by Science Direct. These 'metadata' include author names, titles, publication dates, as well as keywords and abstracts. To synthesise the knowledge production models in the corpus literature, bibliometric analyses were carried out using VOSviewer software [31].

VOSViewer software [32] enables the mapping and visualisation of this metadata in the form of maps from the bibliometric data of the corpus documents (authors, summaries, keywords, year of publication, etc.). If the size of the nodes represents the number of occurrences of the term studied, the distance between the different nodes is an indication of the proximity of the relationship between two terms [31]. The relationships between the keywords or by text analysis of the titles and abstracts of the articles of the corpus were then analysed.

A first study is based on the analysis of co-occurrences of keywords (co-word analysis) in VOSviewer. stated that ‘the number of co-occurrences of keywords indicates the number of publications in which the two keywords occur together in the title, summary, or list of keywords [of the documents of the examination database]’ [31].

Figure 2 represents the four clusters identified by analysing keywords of the documents in the corpus to visualise the similarities between the frequently co-occurring keywords.

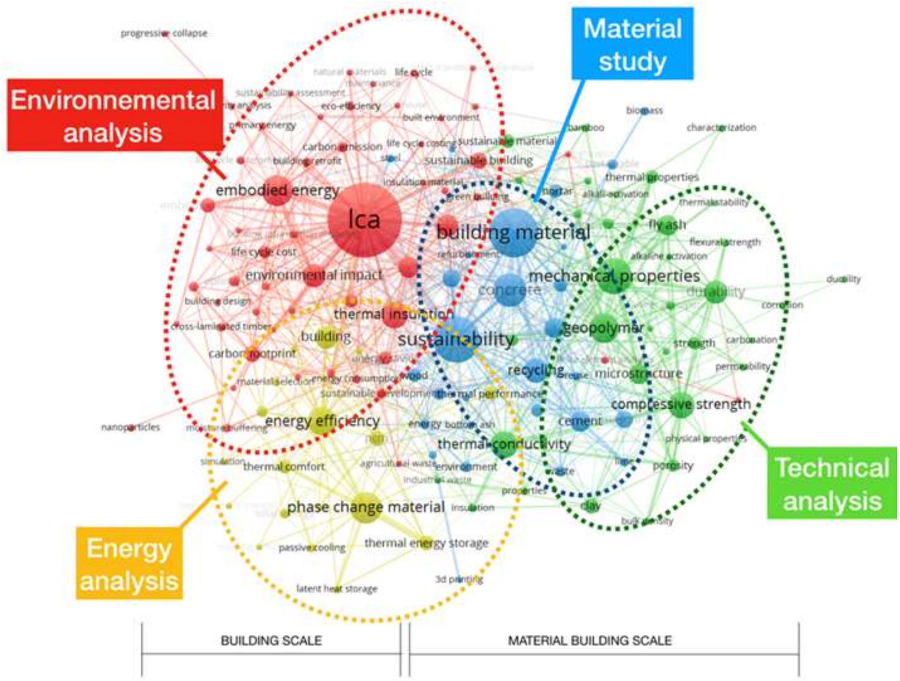


Figure 2. Four clusters identified by analysing keywords.

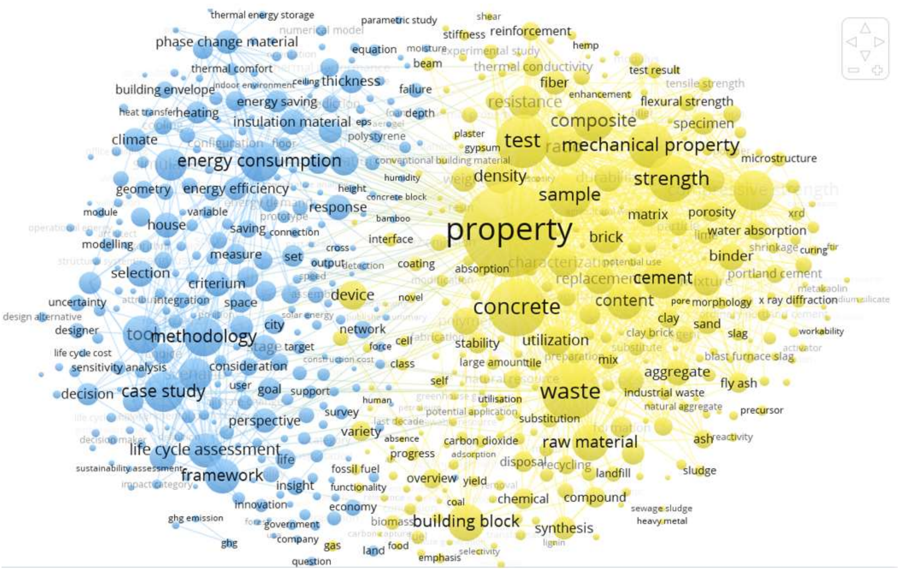


Figure 3. Textual analyses of the titles and summaries.

To complete the study, a textual analysis of the titles and summaries of the 1827 documents of the corpus was analysed using VOSviewer. This involved developing the mapping of recurring terms using the text analysis feature of VOSviewer, which is based on Apache's OpenNLP suite [31]. The following **Figure 3** highlights two clusters. This study makes it possible to be as close as possible to the work of the scientists by analysing their own terminologies.

The years of the weighted publications (average calculation) locate this research between 2014 and 2020. **Figure 4** highlights the homogeneity of the publication dates of this research and confirms the emergence of the recent proliferation of publications on alternative materials.

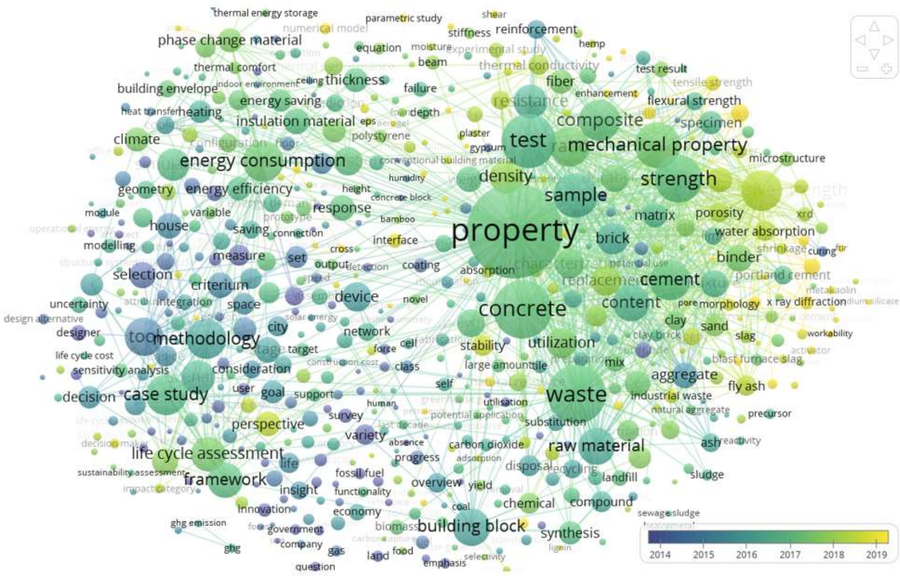


Figure 4. Homogeneity of the publication dates.

3. Results

This section describes the results of bibliometric analyses with thematic trends from keyword mappings supplemented by textual analysis of titles and abstracts.

3.1. Multi-criteria approach

Keyword mapping (**Figure 2**) suggests that literature on alternative building materials is primarily based on environmental, energy, and technical analyses.

The transversal term of this corpus is 'life cycle analysis'. It is positioned in the environmental analysis cluster. Many of the key words associated with environmental analysis are linked to evaluation criteria where computer simulation at the level of the shell and materials is used with economic issues. At a material level, reference is made to biobased materials [37,38], which represent the least processed materials and therefore have the least impact on environmental issues [39,40].

The cluster that refers to energy issues, and more specifically thermal approaches, is an identification of high-performance materials. The choice of materials and the use of computer software for building-scale simulations are also discussed. This research project step is characterised by the analysis of variants to consider the impact of each solution [41,42]. Generally, these studies are at the level of the building to interact with the choices of layout, morphology of the building, and also the choices of equipment (heating, ventilation, etc.).

As for the alternative materials studied (in blue), these are connected to the term 'sustainable'. This corresponds to the objective of the selection of this body of research, which is to demonstrate solutions and strategies for making environmentally friendly materials. This cluster is characterised by the combination of sustainable challenges (sustainability, environment, etc.) and the scale of construction materials according to their family (concrete, cement, brick, wood, steel, masonry, reuse, recycling, mortar, etc.) or raw material (composite, waste, bottom ash, rice husk ash, lime, etc.). The strategies employed vary between the use of agricultural waste recycling of aggregates [42,43] or the substitution of raw materials to manufacture new building materials, which can be biomimetic inspired to imagine new processes or the reuse of waste combination (recycling) [44]. These strategies aim to limit the extraction of resources such as sand [45] or aggregates and also to reduce the carbon footprint of materials. One of the most widely studied materials in this corpus is concrete. It is the subject of many variants with vegetable fibres [46,47], but in reality, it has above all an environmental impact from one of its components: cement. Its manufacturing process (clinker) [48,49] is particularly significant for greenhouse gas emissions.

Concrete studies are regularly associated with the use of more environmentally friendly geopolymers [50,51]. This association is on network mapping in connection with technical analyses (in green). This cluster mainly points towards the technical characteristics (mechanical properties, thermal conductivity, durability, compressive strength, microstructure, porosity, water absorption, permeability, strength, bulk density) intrinsic to building materials (clay, rammed earth, geopolymer concrete, bamboo, etc.) and their components (geopolymer, fly ash, portland cement, blast furnace slag, industrial waste, natural fiber, alkali-activation, etc.). It generally involves ensuring that substitutions of conventional raw materials by waste do not generate structural (solidity) disorders [52–54].

The mapping of key words in scientific documents highlights the need to cross environmental, energy, and technical criteria to develop knowledge of alternative materials. However, this mapping does not clearly establish the positioning of the links between alternative building materials and multidisciplinary approaches (environmental, energy, and technical).

3.2. Alternative materials approaches

Mapping based on textual data (titles and abstracts) of the 1827 documents in the corpus (**Figure 3**) highlights two clusters.

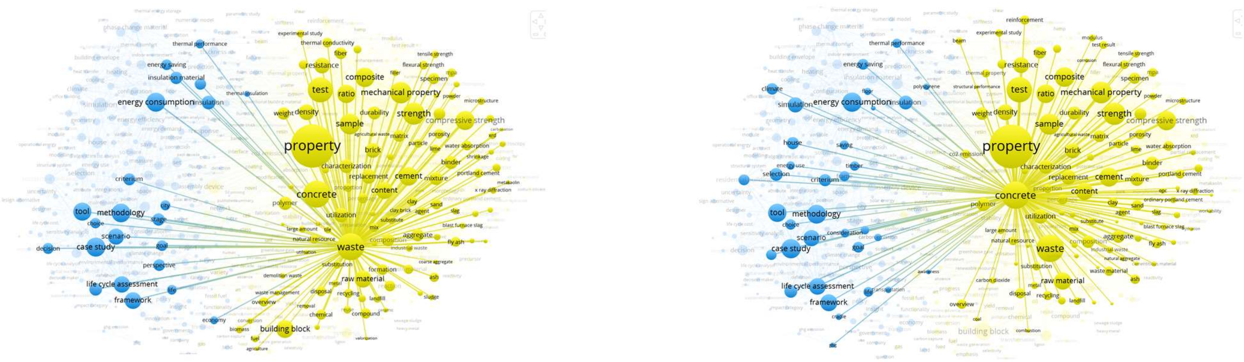
Environmental and climate issues are associated with methodological and analytical approaches (in blue). The aim is to identify the criteria (energy consumption, energy efficiency, thermal performance, indoor environment, life cycle assessment, climate change, etc.) and characteristics of working methods (methodology, scenario, selection, design alternative, etc.). Two approaches emerge: one from case studies (case study) and the other from sensitive analyses (sensitivity analysis) in the form of simulations to evaluate the performance of different constructive solutions. These studies are generally modelled using BIM-oriented software [55]. The mapping reveals questions involving the architectural context (geométry, orientation, variable, software, space, user, decision maker, company, etc.). This cluster represents the modalities of the design process, with its stakeholders (architects, users, designers, etc.), the uses of buildings (houses, residential buildings, office buildings, etc.), and the ideas of choice (selection, criteria, variable, etc.) of constructive systems (roof, floor, wall, envelope, etc.).

The second cluster focuses on the technical characteristics of building materials (brick, concrete, cement, lime, etc.) and raw materials (raw materials, fly ash, sludge, agriculture waste, etc.). It also contains the intrinsic characteristics of the materials (property, characterization, compressive, mechanical property, test, strength, water absorption, porosity, etc.).

From the mapping of the textual analysis (**Figure 3**), the following tables classify building materials and raw materials according to the number of links and their amplitudes (links between the two clusters or links internal to a cluster). These representations, classified by building materials and raw materials, represent trends from publications taken from the corpus studied. They do not make it possible to generalise, rather to identify a position of alternative materials in the face of environmental challenges and the operating methods of design teams when selecting building materials.

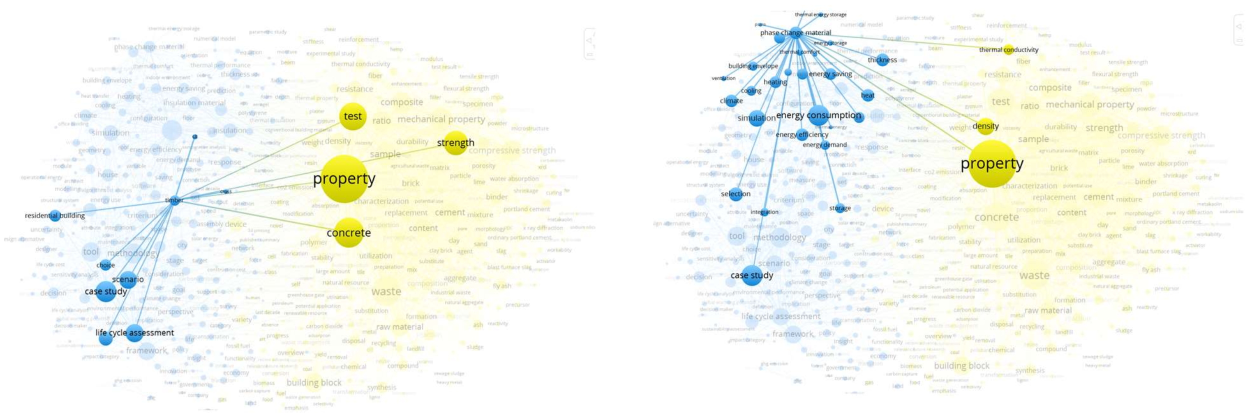
A first position is characterised by numerous links between the two clusters, this means the will to develop a comprehensive questioning that includes environmental issues and working methods specific to the project process. This approach can be called 'integrative' such as in **Figure 5**, as it develops the incorporation of a comprehensive vision of the issues relating to alternative materials. It is interesting to note that the most cited materials are concrete and waste. They are located in cluster 2 with the technical properties of the materials. While wood and phase change materials are positioned in cluster 1 with environmental issues.

A second approach presents links to the technical dimensions and some targeted links to the issues of Life Cycle Analysis within the choices of constructive solutions of shells for brick and of energy consumption and LCA for cement, unrelated to the working methods. This approach can be described as 'additive' such as in **Figure 6**, as these approaches superimpose environmental performance to improve a low carbon-impact score.



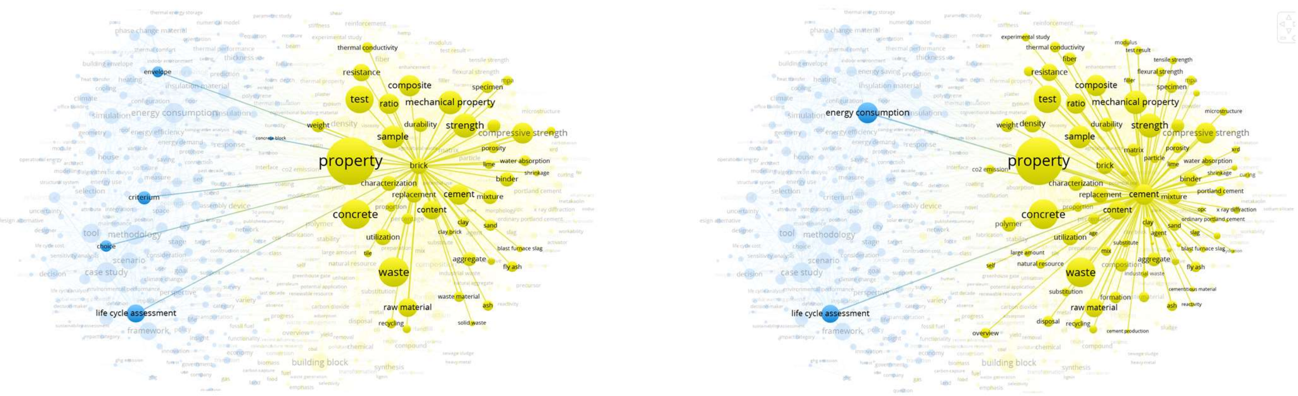
(a) **(b)**

Figure 5. (*Continued*).



(c) **(d)**

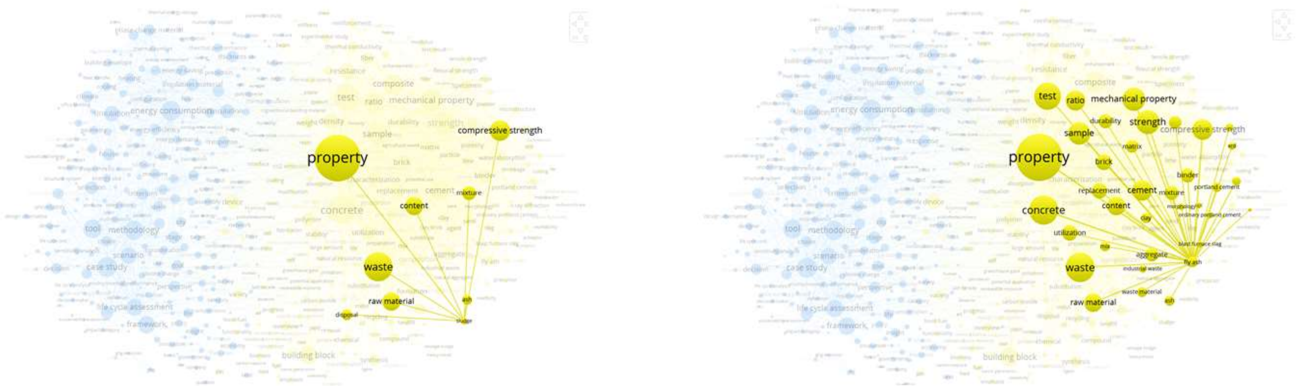
Figure 5. Integrative approach. **(a)** waste; **(b)** concrete; **(c)** wood; **(d)** phase change material.



(a) **(b)**

Figure 6. Additive approach. **(a)** brick; **(b)** cement.

Finally, a third approach shows analyses of materials or raw materials that focus solely on technical issues. This approach can be called ‘subtractive’ such as in **Figure 7**, as it obscures the environmental issues and the specificities of the architectural scale. This approach mainly involves raw materials that have a substitution role. This research is the most recent, which may explain the low number of redundancies.



(a) **(b)**

Figure 7. (*Continued*).

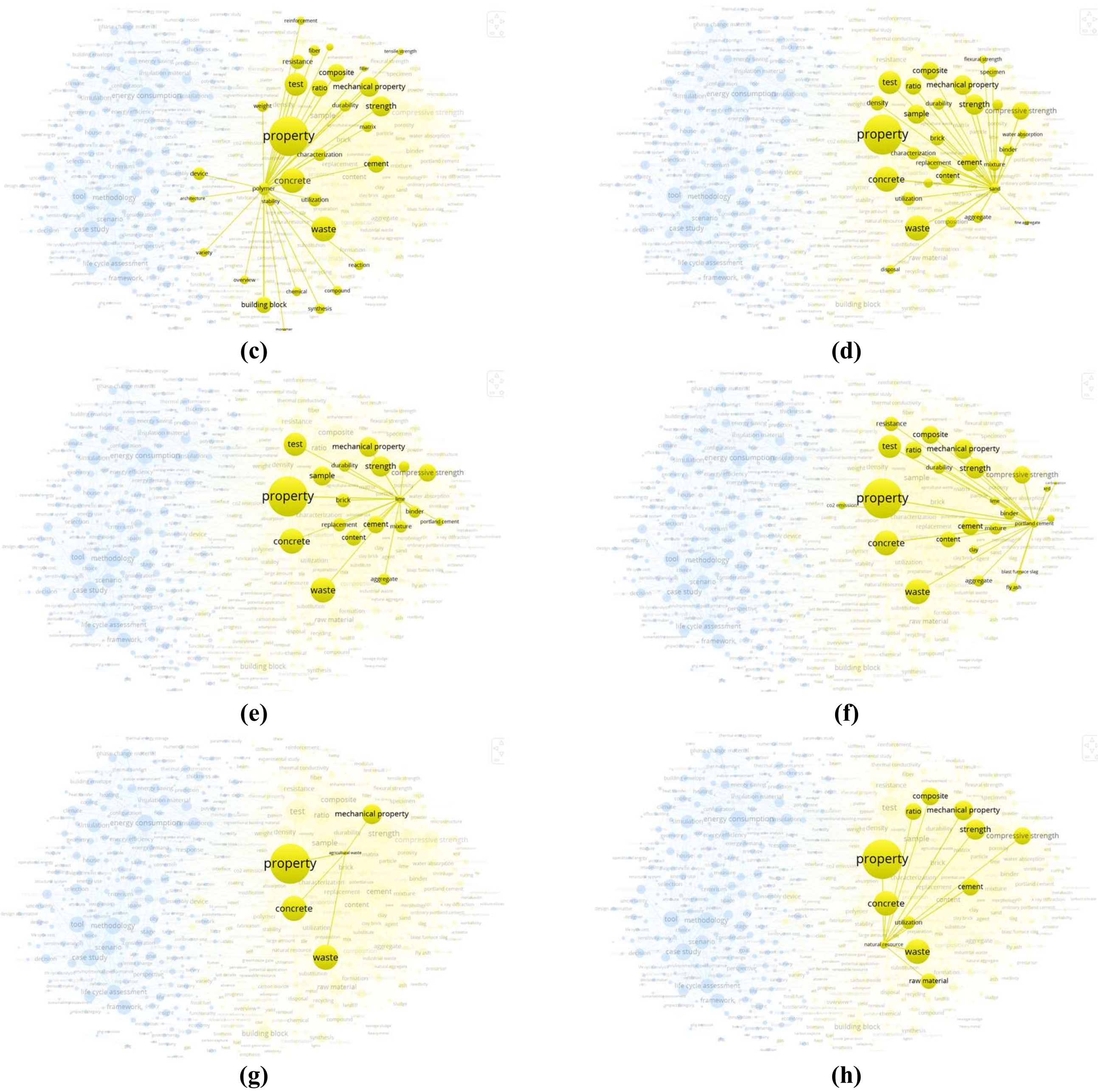


Figure 7. Subtractive approach. **(a)** mud; **(b)** fly ash; **(c)** polymer; **(d)** lime; **(e)** waste; **(f)** Portland cement; **(g)** agricultural waste; **(h)** natural resources.

4. Discussion

Using bibliometric analysis, this paper addressed the emergence of literature on alternative building materials. This section highlights the limitations and presents interpretations of the results.

4.1. Limitations of study

This study focused on the theme of 'alternative building materials'. The scope of this topic may have led to ambivalence in the selection of the documents that make up the corpus. A second limitation stems from our reliance on indexing Science Direct to source the documents, which impacted the availability of data. This study would have benefited from integrating documents from other platforms such as Google Scholar, Scopus, etc. In the absence of the exhaustiveness of the number of documents listed, the selection here focused on the quality of Science Direct publications with a peer selection.

4.2. Interpretation

This article generated a substantial foundation of knowledge and experiences on alternative building materials from 1827 documents indexed by Science Direct. The study showed that 90% of the documents in our corpus were published in the last ten years. An acceleration of publications emerged in 2010. This interest is linked to the climate context with the consideration of environmental issues [56] and their increasingly significant integration into building regulations. Also during this period, the development of databases on the LCA of building materials was strengthened [57], and computer tools integrating environmental simulations became widespread. The current context at the heart of the environmental, ecological, digital, etc. transitions suggests that an ever-growing number of publications on alternative materials will be developed in the coming years. Over the next decade, the number of publications could more than double in size. This reflects the rapid evolution of a new approach to improving building materials by reducing their environmental impacts within the architectural design process.

This study identified the positions on alternative materials in the face of environmental challenges and their integration into the architectural design process. This makes it possible to develop a comprehensive vision that identifies characteristics common to isolated experiments, generally classified by types of materials handled in a rather piecemeal fashion. The aim of the systemic approach proposal is to allow an understanding of current practices, to position the main issues and to anticipate their orientations. The definition of the three approaches (integrative, additive, and subtractive) shows that the aims of alternative materials are numerous. Each experiment defines its own scope of action. In this context, it is not appropriate to transcribe a generic definition of an alternative material but rather to identify the different positions and issues. The aim is to determine the environmental, social, and economic significance of the manufacture of alternative materials in a given territory. It is not because it is an alternative material but that it in fact participates in a greater ambition for sustainable development, introduced in 1987 by the Brundtland report (Our Common Future), which defines it as ‘development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ [58].

Some approaches, such as integrative approaches, seek a territorial anchorage to develop a circular economy [59], working with local stakeholders, working for a building that respects the environment, both in the choice of layout (orientation, sunshine, etc.) of morphology (thermal efficiency, material economy, etc.) of materiality (performance levels of walls, LCA, etc.). These approaches are evolving towards a paradigm shift, with societal issues placing climate and environmental issues at the centre of design.

Additive approaches are firmly rooted in today’s society. They involve changing existing materials to improve their environmental scores. Today, two criteria are particularly important: the carbon factor and energy consumption. The manufacture of these materials meets future regulatory requirements while maintaining the current operating modes. Finally, subtractive approaches are in keeping with additive approaches, as they focus on the ability to substitute energy-intensive raw materials and/or materials with a large carbon footprint with less impactful raw materials (waste, bio-based materials, etc.). These two positions raise the question of the close link between the choices of environmental performance expressed by future regulations and the orientation of the alternatives studied. For example, the inclusion of the 'carbon sink' phenomenon in the calculation of LCAs for construction materials has largely encouraged the addition of avengeable fibres or agricultural waste in the composition of bricks, concrete, etc. without, however, studying the real impact of supplying these raw materials, such as their transport.

5. Conclusion

This study has rigorously examined the potential and challenges of alternative building materials through a detailed bibliometric analysis of 1827 publications. We have uncovered that while these materials promise significant environmental benefits, integrating them into mainstream construction practices presents substantial hurdles. These challenges span technical feasibility, economic viability, and regulatory acceptance, each of which requires dedicated solutions to overcome.

Our findings reveal that the adoption of alternative materials is not merely a technical decision but a reflection of broader societal values and commitments toward sustainability. The integrative, additive, and subtractive approaches each map out different pathways for incorporating ecological considerations into building practices, influencing the industry's evolution toward sustainability. These approaches are indicative of the depth of systemic change needed—a shift that involves rethinking not only materials but also the frameworks within which they are used.

To navigate these complexities, we advocate for strengthened collaborations that bridge the gap between research and industry, underpinned by robust partnerships among scientists, industry experts, and policymakers. We emphasize the critical role of education and policy reform in fostering a culture that is receptive to innovative, sustainable materials. Incentives should be strategically designed to support the adoption of these materials, ensuring that they are not only technically and economically feasible but also aligned with regulatory frameworks.

Looking ahead, it is imperative that future research focus on creating adaptable frameworks for the practical application of these materials, considering economic, logistical, and scalability factors. Understanding their performance across different environmental and geographic conditions will also be crucial. Bibliometric studies are essential for providing the necessary perspective on ongoing developments, allowing us to position and reposition challenges within an informed context.

Ultimately, the integration of innovative building materials into the construction industry is essential for meeting global sustainability goals. It requires a concerted effort that spans multiple sectors and disciplines. By committing to this comprehensive approach, we can lay the groundwork for a construction industry that not only adapts to but also thrives in the face of ecological challenges, paving the way for a more sustainable future for generations to come.

Conflict of interest: The author declares no conflict of interest.

References

1. Brown JH, Burger JR, Burnside WR, et al. Macroecology meets macroeconomics: Resource scarcity and global sustainability. Ecological Engineering. 2014; 65: 24-32. doi: 10.1016/j.ecoleng.2013.07.071
2. Ruuska A, Häkkinen T. Material Efficiency of Building Construction. Buildings. 2014; 4(3): 266-294. doi: 10.3390/buildings4030266
3. Hansen K, Braungart M, Mulhall D. Resource Repletionresourcerepletion, Role of Buildings. In: Loftness V, Haase D. (editors). Sustainable Built Environments. Springer; 2013.
4. Li L. Integrating climate change impact in new building design process: A review of building life cycle carbon emission assessment methodologies. Cleaner Engineering and Technology. 2021; 5: 100286. doi: 10.1016/j.clet.2021.100286
5. UNEP. Global Status Report for Buildings and Construction 2019. UNEP; 2019.
6. Zhang X, Wang F. Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China. Energy and Buildings. 2017; 155: 404-413. doi: 10.1016/j.enbuild.2017.09.049
7. Orsini F, Marrone P. Approaches for a low-carbon production of building materials: A review. Journal of Cleaner Production. 2019; 241: 118380. doi: 10.1016/j.jclepro.2019.118380
8. González MJ, García Navarro J. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact. Building and Environment. 2006; 41(7): 902-909. doi: 10.1016/j.buildenv.2005.04.006
9. Gama EM, Wamuziri S, Sloan B. The use of alternative building materials in developing countries: Addressing challenges faced by stakeholders. In: Proceedings of the World Construction Conference 2012—Global Challenges in Construction Industry; 28-30 June 2012; Colombo, Sri Lanka.
10. Li X, Qin D, Hu Y, et al. A systematic review of waste materials in cement-based composites for construction applications. Journal of Building Engineering. 2022; 45: 103447. doi: 10.1016/j.jobe.2021.103447
11. Thomas BS, Yang J, Mo KH, et al. Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: A comprehensive review. Journal of Building Engineering. 2021; 40: 102332. doi: 10.1016/j.jobe.2021.102332
12. Salas DA, Ramirez AD, Rodríguez CR, et al. Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review. Journal of Cleaner Production. 2016; 113: 114-122. doi: 10.1016/j.jclepro.2015.11.078
13. Jannat N, Latif Al-Mufti R, Hussien A, et al. Utilisation of nut shell wastes in brick, mortar and concrete: A review. Construction and Building Materials. 2021; 293: 123546. doi: 10.1016/j.conbuildmat.2021.123546
14. Amran M, Murali G, Khalid NHA, et al. Slag uses in making an ecofriendly and sustainable concrete: A review. Construction and Building Materials. 2021; 272: 121942. doi: 10.1016/j.conbuildmat.2020.121942
15. Ramachandran D. Green Concrete mix using solid waste and nanoparticles as alternatives—A review. Construction and Building Materials. 2018; 162: 96-103. doi: 10.1016/j.conbuildmat.2017.11.174
16. Ramos Huarachi DA, Gonçalves G, de Francisco AC, et al. Life cycle assessment of traditional and alternative bricks: A review. Environmental Impact Assessment Review. 2020; 80: 106335. doi: 10.1016/j.eiar.2019.106335
17. Sotayo A, Bradley D, Bather M, et al. Review of state of the art of dowel laminated timber members and densified wood materials as sustainable engineered wood products for construction and building applications. Developments in the Built Environment. 2020; 1: 100004. doi: 10.1016/j.dibe.2019.100004
18. Petersen AK, Solberg B. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics. 2005; 7: 249-259.
19. Li Y, Zhang Y, Yang Z, et al. Waterborne coatings with sub-ambient cooling under direct sunlight-part I: Optical properties and cooling effect measurements. Solar Energy Materials and Solar Cells. 2020; 217: 110672. doi: 10.1016/j.solmat.2020.110672

20. Guldentops G, Ardito G, Tao M, et al. A numerical study of adaptive building enclosure systems using solid-solid phase change materials with variable transparency. Energy and Buildings. 2018; 167: 240-252. doi: 10.1016/j.enbuild.2018.02.054
21. Sameer H, Bringezu S. Life cycle input indicators of material resource use for enhancing sustainability assessment schemes of buildings. Journal of Building Engineering. 2019; 21: 230-242. doi: 10.1016/j.jobe.2018.10.010
22. Yousefi M, Khandestani R, Gharaei-Moghaddam N. Flexural behavior of reinforced concrete beams made of normal and polypropylene fiber-reinforced concrete containing date palm leaf ash. Structures. 2022; 37: 1053-1068. doi: 10.1016/j.istruc.2022.01.067
23. Ahmad MR, Chen B, Yousefi Oderji S, et al. Development of a new bio-composite for building insulation and structural purpose using corn stalk and magnesium phosphate cement. Energy and Buildings. 2018; 173: 719-733. doi: 10.1016/j.enbuild.2018.06.007
24. Wang Y, Rasheed R, Jiang F, et al. Life cycle assessment of a novel biomass-based aerogel material for building insulation. Journal of Building Engineering. 2021; 44: 102988. doi: 10.1016/j.jobe.2021.102988
25. Teoh WP, Chee SY, Habib NZ, et al. Recycling of treated alum sludge and glycerine pitch in the production of eco-friendly roofing tiles: Physical properties, durability, and leachability. Journal of Building Engineering. 2022; 52: 104387. doi: 10.1016/j.jobe.2022.104387
26. Belfiore CM, Amato C, Pezzino A, et al. An end of waste alternative for volcanic ash: A resource in the manufacture of ceramic tiles. Construction and Building Materials. 2020; 263: 120118. doi: 10.1016/j.conbuildmat.2020.120118
27. Ayikoe Tettey UY, Dodoo A, Gustavsson L. Carbon balances for a low energy apartment building with different structural frame materials. Energy Procedia. 2019; 158: 4254-4261. doi: 10.1016/j.egypro.2019.01.801
28. Martínez-García C, González-Fonteboa B, Carro-López D, et al. Assessment of mussel shells building solutions: A real-scale application. Journal of Building Engineering. 2021; 44: 102635. doi: 10.1016/j.jobe.2021.102635
29. Beattie C. Decarbonising new city precincts: A case study in Perth, Western Australia. Renewable Energy. 2014; 67: 64-72. doi: 10.1016/j.renene.2013.11.042
30. Reza B, Sadiq R, Hewage K. Sustainability assessment of flooring systems in the city of Tehran: An AHP-based life cycle analysis. Construction and Building Materials. 2011; 25(4): 2053-2066. doi: 10.1016/j.conbuildmat.2010.11.041
31. Van Eck NJ, Waltman L. Visualizing bibliometric networks. In: Ding Y, Rousseau R, Wolfram D (editors). Measuring Scholarly Impact: Methods and Practice. Springer International Publishing; 2014.
32. van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics. 2009; 84(2): 523-538. doi: 10.1007/s11192-009-0146-3
33. Det Udomsap A, Hallinger P. A bibliometric review of research on sustainable construction, 1994-2018. Journal of Cleaner Production. 2020; 254: 120073. doi: 10.1016/j.jclepro.2020.120073
34. Santos WF, Quattrone M, John VM, et al. Roughness, wettability and water absorption of water repellent treated recycled aggregates. Construction and Building Materials. 2017; 146: 502-513. doi: 10.1016/j.conbuildmat.2017.04.012
35. Zhao H xiang, Magoulès F. A review on the prediction of building energy consumption. Renewable and Sustainable Energy Reviews. 2012; 16(6): 3586-3592. doi: 10.1016/j.rser.2012.02.049
36. Laurie AP. Building Materials made of Waste Materials. Nature. 1923; 112(2826): 956-957. doi: 10.1038/112956b0
37. Aureliano Fd'S, Costa AApF, Júnior IF, Pedroso Rd'O. Manufacture of structural blocks of concrete with waste tire rubbers. Procedia Manufacturing. 2019; 38: 464-470. doi: 10.1016/j.promfg.2020.01.059
38. Galimshina A, Moustapha M, Hollberg A, et al. Bio-based materials as a robust solution for building renovation: A case study. Applied Energy. 2022; 316: 119102. doi: 10.1016/j.apenergy.2022.119102
39. Palumbo M, Lacasta AM, Giraldo MP, et al. Bio-based insulation materials and their hygrothermal performance in a building envelope system (ETICS). Energy and Buildings. 2018; 174: 147-155. doi: 10.1016/j.enbuild.2018.06.042
40. Žigart M, Kovačič Lukman R, Premrov M, et al. Environmental impact assessment of building envelope components for low-rise buildings. Energy. 2018; 163: 501-512. doi: 10.1016/j.energy.2018.08.149
41. Zeitz A, Griffin CT, Dusicka P. Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages. Energy and Buildings. 2019; 199: 126-133. doi: 10.1016/j.enbuild.2019.06.047
42. Cusenza MA, Guarino F, Longo S, et al. An integrated energy simulation and life cycle assessment to measure the operational and embodied energy of a Mediterranean net zero energy building. Energy and Buildings. 2022; 254: 111558. doi: 10.1016/j.enbuild.2021.111558

43. Zawrah MF, Gado RA, Feltin N, et al. Recycling and utilization assessment of waste fired clay bricks (Grog) with granulated blast-furnace slag for geopolymer production. Process Safety and Environmental Protection. 2016; 103: 237-251. doi: 10.1016/j.psep.2016.08.001
44. Corinaldesi V, Giuggiolini M, Moriconi G. Use of rubble from building demolition in mortars. Waste Management. 2002; 22: 893-899. doi: 10.1016/S0956-053X(02)00087-9
45. Bisht A. Sand futures: Post-growth alternatives for mineral aggregate consumption and distribution in the global south. Ecological Economics. 2022; 191: 107233. doi: 10.1016/j.ecolecon.2021.107233
46. Bunzel F, Wisner G, Stammen E, et al. Structural sandwich composites out of wood foam core and textile reinforced concrete sheets for versatile and sustainable use in the building industry. Materials Today: Proceedings. 2020; 31: S296-S302. doi: 10.1016/j.matpr.2020.01.382
47. Göswein V, Silvestre JD, Lamb S, et al. Invasive alien plants as an alternative resource for concrete production—multi-scale optimization including carbon compensation, cleared land and saved water runoff in South Africa. Resources, Conservation and Recycling. 2021; 167: 105361. doi: 10.1016/j.resconrec.2020.105361
48. Humbert PS, Castro-Gomes JP, Savastano H. Clinker-free CO_2 cured steel slag based binder: Optimal conditions and potential applications. Construction and Building Materials. 2019; 210: 413-421. doi: 10.1016/j.conbuildmat.2019.03.169
49. Vashistha P, Singh SK, Dutt D, et al. Sustainable utilization of paper mill solid wastes via synthesis of nano silica for production of belite based clinker. Journal of Cleaner Production. 2019; 224: 557-565. doi: 10.1016/j.jclepro.2019.03.207
50. Akbar A, Farooq F, Shafique M, et al. Sugarcane bagasse ash-based engineered geopolymer mortar incorporating propylene fibers. Journal of Building Engineering. 2021; 33: 101492. doi: 10.1016/j.jobe.2020.101492
51. Alonso MM, Gascó C, Morales MM, et al. Olive biomass ash as an alternative activator in geopolymer formation: A study of strength, radiology and leaching behaviour. Cement and Concrete Composites. 2019; 104: 103384. doi: 10.1016/j.cemconcomp.2019.103384
52. Bajracharya RM, Manalo AC, Karunasena W, et al. An overview of mechanical properties and durability of glass-fibre reinforced recycled mixed plastic waste composites. Materials & Design (1980-2015). 2014; 62: 98-112. doi: 10.1016/j.matdes.2014.04.081
53. Binici H, Aksogan O, Demirhan C. Mechanical, thermal and acoustical characterizations of an insulation composite made of bio-based materials. Sustainable Cities and Society. 2016; 20: 17-26. doi: 10.1016/j.scs.2015.09.004
54. Suksiripattanapong C, Jenpiyapong K, Tiyasangthong S, et al. Mechanical and thermal properties of lateritic soil mixed with cement and polymers as a non-bearing masonry unit. Case Studies in Construction Materials. 2022; 16: e00962. doi: 10.1016/j.cscm.2022.e00962
55. Ahmad T, Aibinu A, Thaheem MJ. BIM-based Iterative Tool for Sustainable Building Design: A Conceptual Framework. Procedia Engineering. 2017; 180: 782-792. doi: 10.1016/j.proeng.2017.04.239
56. Ahmed N, Abdel-Hamid M, Abd El-Razik MM, et al. Impact of sustainable design in the construction sector on climate change. Ain Shams Engineering Journal. 2021; 12(2): 1375-1383. doi: 10.1016/j.asej.2020.11.002
57. Wernet G, Bauer C, Steubing B, et al. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment. 2016; 21(9): 1218-1230. doi: 10.1007/s11367-016-1087-8
58. IEA. Global Status Report for Buildings and Construction 2019. IEA; 2019.
59. Predeanu G, Slăvescu V, Bălănescu M, et al. Coal bottom ash processing for capitalization according to circular economy concept. Minerals Engineering. 2021; 170: 107055. doi: 10.1016/j.mineng.2021.107055

ACADEMIC

Academic Publishing Pte. Ltd.

Add: 73 Upper Paya Lebar Road #07-02B-01 Centro Bianco Singapore 534818
Tel: +65 83184869
E-mail: editorial_office@acad-pub.com
Web: http://ojs.acad-pub.com/