Examining the barriers to the adoption of IoT-based technologies in green buildings

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Abstract: Although the adoption of Internet-of-Things (IoTs) within Green Buildings (GBs) has elicited significant attention from researchers and practitioners in the construction sector, few studies have investigated the barriers to its implementation. To bridge this gap, this study aimed to identify and analyze the barriers to the adoption of IoTs in GBs through the lens of seasoned experts in the Hong Kong construction sector. A hybrid of systematic reviews, expert interviews, and Social Network Analysis was studied. The results revealed that: (1) twenty-six barriers impede the adoption of IoTs within GBs, and these barriers can be categorized into seven clusters; (2) the most significant barriers include "political/regulatory" and "security" categories; and (3) "cybersecurity and data risks," "concerns over the protection of intellectual

property," "fewer GB Codes/regulations available," "documentation requirements," and "uncertain government's policies and absence of government support" are the most critical impediments. The findings would pave the way for relevant decision-makers to adopt further productive measures towards promoting the adoption of IoT-based technologies in GBs, thereby expediting the embracement of the sustainability paradigm in the construction sector.

Keywords: Green Buildings; Green Construction; Sustainability; Internet of Things; Barriers; Social Network Analysis.

1. INTRODUCTION

Building industry is responsible for 38.2% of global energy consumption(Hadri et al., 2021). The majority of energy in buildings comes from heating, cooling, lighting and other environmental factors. In order to achieve sustainable and green buildings, it is important to control and manage this energy(Krishnamurthi and Dhanalekshmi, 2020). This necessitates the use of novel approaches in data acquisition, data pre-processing, prediction, optimization, and automation of appliances in accordance with environmental factors to optimize their performance and minimize energy usage (Schmidt and Åhlund, 2018). Internet of Things (IoTs), which consists of sensors, software, and other electronic devices connected to each other through a smart network, is a novel framework for boosting the functionality of systems in several areas, including the construction sector (Stergiou et al., 2018). In recent years, applications of IoT-based technologies have garnered attention in several areas of construction works such as construction safety (Kanan et al., 2018, Khan et al., 2022, Yang et al., 2020), infrastructure management (Brundu et al., 2016, Chen et al., 2019, Marques et al., 2019) and the development of smart cities (Atitallah et al., 2020, Majeed et al., 2021). This is also consistent with Hong Kong. Hong Kong is known as one of the highest population densities in the world (Jaillon and Poon, 2008). This developed various challenges for the Hong Kong construction industry including safety, labor shortages, time, and environmental protection (Li et al., 2016).

To address these problems within sustainable and green context, the IoT is anticipated to gain traction as a viable solution in Hong Kong. From 2017, The Hong Kong Convention and Exhibition center updated his Building management system (BMS) to integrate IoT network with their collection of data including temperature, humidity, internal air quality, and water leakage (Chung et al., 2023). Todays, Hong Kong aims to use IoT in various green aspects of Hong Kong construction industry including prefabrication (Li et al., 2016), Modular construction (Zhai et al., 2019) and safety management (Chung et al., 2023).

IoT-based technologies in a GB collect and process the data regarding consumed energy and materials, produced energy, cost of the energy and materials, and residents' behavior and comfort to efficiently manage and plan the energy system of the building (Jain et al., 2020). The integration of IoT-based technologies in GBs provides valuable real-time information to building decision-makers regarding the performance, security, and safety of buildings such as elevators and lighting systems. The advantages of integrating IoT-based technologies in GBs include energy savings, automation, personalization, and prosperous business opportunities (Jain et al., 2020). However, integrating IoT-based technologies into GBs encounters many challenges such as the quality of data obtained by the sensors, computational time, fault tolerance, middleware of the IoT system, unification of the IoT parts, security issues, possibility of cyber-attacks, susceptibility of the sensors to damages, mobility and accessibility of the sensors, and lack of universal standards and established agreed-upon architecture for integration of IoT in GBs (Jain et al., 2020, Krishnamurthi and Dhanalekshmi, 2020).

Integrating IoT in GBs requires a robust framework. However, the development of robust frameworks for IoT systems is still in its infancy. Researchers have presented architectures to integrate IoT in GBs. Marinakis and Doukas (2018) suggested a framework consisting of five modules that collect weather data, energy costs, behavior of the occupants, and energy generation. The collected data are processed by semantic web technologies to provide

information to decision-makers on the best actions for optimized energy consumption. Krishnamurthi and Dhanalekshmi (2020) provided an architecture of GB-based on IoT, which consists of four interconnected layers: (1) capillary network layer or sensors, (2) access layer including Internet, Wi-Fi, and Bluetooth, (3) middleware layer or data processing unit, and (4) service layer. The primary purpose of this network is to reduce the consumption of water, electricity, and gas (Barbon et al., 2016). Even though these studies have brought about significant advancements in the field for concerned decision-makers and researchers, a scrupulous investigation into the barriers to the implementation of IoTs within GBs has received minimal attention. In fact, the integration of IoT-based technologies into the construction and maintenance of GBs is intertwined with impediments; thus, it is imperative to conduct research on tackling the barriers regarding IoT adoption in this sector. Recognizing the barriers and attempting to overcome them will pave the way toward significantly reducing energy consumption and reliance on fossil fuels, mitigating the generation of GHGs and their influence on climate change, and making sustainable buildings resilient. In addition, it can significantly improve resource management, leading to reduced environmental impact and cost savings. Additionally, it enhances living conditions, safety, and security for occupants. Understanding these barriers can help policy makers, government, and industry stakeholders develop supportive regulations and standards. Furthermore, Recognizing the interconnection between barriers can help all stakeholders of the projects to invest more on addressing the most important and connected barriers. Doing so enables them to significantly reduce time, energy, and cost and it can also reduce other related barriers. Overall, Recognizing the main IOT barriers and its interconnections and addressing them can lead to broader IOT integration and create a more sustainable, efficient, and healthy built environment. That said, this research aims to tackle the following research question (RQ):

RQ. What are the barriers affecting the adoption of IoTin GBs and how could the interrelationships existing among them be unraveled?

To tackle the above-mentioned RQ, this study aims to realize the following objectives:

- Identify the critical barriers to adopting IoT-based technologies in GBs
- (2) Examine and analyze the interrelationship between identified barriers and the level of prioritization of IoT-based technologies in GBs.

To take full note of the above-mentioned research objectives, this study employs a hybrid methodological approach, including an extensive review, expert interviews, and the utilization of Social Network Analysis (SNA). Data was collected from qualified respondents in the Hong Kong construction industry. The major contributions of are twofold. Firstly, the barriers and corresponding categories impeding the adoption of IoT-based technologies in GBs are identified. By identifying and categorizing these barriers, this research aims to lay a solid foundation to help stakeholders recognize and address the specific challenges that impede the widespread adoption of IoT in green buildings. Secondly, the interrelationships between the identified barriers by conducting different types of network analysis are determined. This involves mapping how these barriers influence and interact with one another, providing a deeper understanding of their complex interdependencies. By applying these network analysis methods, the research reveals the intricate web of interactions among the barriers, enabling more strategic and effective interventions to advance the adoption of IoT technologies in green buildings.

The study offers several implications as follows. It categorizes barriers to IoT adoption in green buildings to help project managers prioritize and allocate resources efficiently. It also reveals interactions and influences among barriers, aiding in their prioritization. Moreover, the study emphasizes the importance of stakeholder engagement and collaboration in addressing

specific barriers. Additionally, the data-driven approach supports the monitoring and evaluation of the effectiveness of initiatives aimed at mitigating these barriers.The remainder of this paper is organized as follows. Section 2 reviews the current literature on the studied topic, and the methodological approach adopted in this research is discussed in section 3. Sections 4 and 5 report the results and relevant findings, respectively. The implications and limitations of this study are presented in sections 6 and 7, respectively. Finally, the conclusions are presented in section 8.

2. LITERATURE REVIEW

Conventional buildings have offered desired living spaces to their occupants for many decades. However, with growing demands for environmentally friendly and sustainable buildings, along with the higher energy consumption and significant GHG emissions of conventional buildings, a visible shift towards the adoption of GB practices has been witnessed (Kineber et al., 2022). This paradigm shift in the construction industry offers unique construction methodologies, the use of new innovative building materials (Fazeli et al., 2022), considerable reduction in energy consumption and thermal comfort for its occupants (Omer, 2008), standards and regulatory support to concerned stakeholders (Bamgbade et al., 2019), and other prominent facets of sustainability.

As per, Hussain et al., (2023), and in analogous alignment to the project life cycle phases, following sub-headings are designed to explain the reviewed literature in an organized manner.

2.1. Use of Advanced Technologies

Moreover, modern-day construction without the use of advanced technologies is almost non-existent (Banihashemi et al., 2022). The construction industry has witnessed the evolution of

156 information technologies in recent decades (Fazeli et al., 2020). Table 1 presents the summary
157 of reviewed literature in detail.

158 Insert Table 1 here

159 Furthermore, smart sensor-based building features to facilitate intelligent decision-making for
160 building occupants according to their preferences (Durdyev et al., 2022). With these boons, the
161 use of IoT-based technologies in GBs also experiences some critical barriers to its effective
162 implementation. With this preamble, this study aimed to explore the barriers pertaining to the
163 effective implementation of IoT-based technologies in the context of GBs. In the following
164 paragraphs, recent literature on the studied topic is reviewed in detail.

165 **2.2. Issues in Technology enabled Green Building Design**

166 From the perspective of design stage for GB, integration of IoT technologies yields a unique
167 set of pertinent issues. Chen et al., (2023) explored integration of BIM and IoT for Sustainable
168 GB and concluded that the existing research is limited to only a few phases of building the
169 lifecycle and should be extended to all the stages of building lifecycle. In another study
170 conducted by Liu et al., (2019), an information management framework is proposed using
171 block chain technology and BIM. The study suggests that the framework should be
172 implemented for broader applications instead of focusing on the frequent building energy
173 optimization research.

174 **2.3. Legal Considerations for Green Buildings**

175 Yeon et al. (2018) explored the legal side of the GB industry and found that building smart home
176 projects require special legal considerations such as data security, privacy of the occupants,
177 and knowledge-sharing protocols. In the existing state, this aspect lacks adequate legal
178 frameworks to support green and smart home construction, thus contributing to the design of a
179 legal framework for the same is essential. Maksimovic (2018) believes that for a green future,
180 that is, for sustainable development, IoT needs to be seen from a greener perspective. In this

regard, green-IoT-based processes, enablers, principles, and roles must be explored to improve the quality of life of building occupants and future generations.

2.4. Effectiveness of Green Features across Building Stages

According to GhaffarianHoseini et al. (2019), the effectiveness of green features is a matter of importance not only for the construction stage of the building but also for the post-construction stage. The effectiveness of IoT-enabled green features is typically gauged at this stage, i.e., the building stage. Therefore, the authors integrated the N-dimensions of building information modeling (ND BIM) into the knowledge base of building management systems to inspect post-construction energy efficiency. Yin et al. (2019) considered that the continuous monitoring of GB parameters is essential for ensuring sustainability. As such, IoT data, in conjunction with geographic information system (GIS) and building information modeling (BIM) tools for improved visualization, have shown promising results in monitoring the performance of GBs and providing an opportunity for concerned stakeholders to make well-informed decisions.

2.5. Maintenace Management for the Green Buildings

Ismail (2020) considered the maintenance management of GB projects as one of the critical components for the growth of the green-construction industry. Because technology-enabled solutions for green buildings require close monitoring, the author developed an information and communication technology (ICT)-based approach for managing the maintenance of green buildings. Kluczek et al. (2021) applied lifecycle measures to an integrated method of environmental sustainability assessment using RFID and wireless sensor networks. Their study output promotes an integrated method to support decision-making processes in the domain of environmental sustainability assessment. Wu et al. (2021) conducted a detailed topical network-based analysis of the literature on GBs of the preceding three decades and visualized global research trends. Based on the literature analysis, GB design, energy saving, GB rating system,

205 life cycle evaluation, incentives and hindrances, post-occupancy evaluation, GB technologies,
206 GB market, and management aspects of GB are the prominent research directions, with an
207 emphasis on the employment of digital technologies in this context.

208 **2.6. Lack Evaluation Approaches for GB IoT solutions**

209 Metwally et al. (2022) opined that there is a lack of approaches for evaluating IoT solutions in
210 the context of GBs. Therefore, using an interdisciplinary framework, the authors developed an
211 IoT assessment method for energy-efficient buildings, which signifies the need for current
212 work. Debrah et al. (2022) presented a detailed literature review on the application of artificial
213 intelligence (AI) for GBs. Their study found a clear gap in the body of knowledge regarding
214 AI applications in the GBs. The authors suggested that in addition to the legal, ethical, and
215 moral aspects of AI in GBs, advanced technologies such as digital twins, AI of things,
216 blockchain, robotics, and 4D printing should be explored to enhance the sustainability and
217 efficiency of the building and construction sector. Olanrewaju et al. (2022) reviewed the
218 literature on the application of BIM in the context of GB certification systems. The results of
219 the study revealed that the majority of the literature (i.e., around 70% of the total) focused on
220 the energy consumption of GB, thus, indicating the significance and popularity of research on
221 technology implementation in this domain. Lawal and Rafsanjani (2021) identified the latest
222 trends, benefits, risks, and challenges of IoT implementation in residential and commercial
223 buildings.

224 **2.7. Main Challenges and Research Gaps**

225 The main challenges identified are the integration of various IoT-based technologies with
226 different capabilities, data storage and processing, privacy, and security risks. Despite other
227 studies that emphasize the need for structured legal protocols and regulations, Bortone et al.
228 (2022) concluded that at the household level in the United Kingdom, there exist apparent gaps

229 in the regulation and policies on the application of green technologies, which still need rigorous
230 efforts for effective implementation. Malik and Kushwah (2022) conducted a survey to determine
231 the needs and design requirements of next-generation IoT networks from a green IoT
232 perspective. Based on a systematic review together with experts' interviews (which will be
233 elaborated on in the Methodology section), the barriers impeding the adoption of IoT in
234 construction are summarized in Table 2, along with the corresponding categories and
235 definitions. Based on the identified categories and their definitions, it is believed that, in
236 modern-day construction, where multi-disciplinary research is extremely vital to resolve
237 complex nature of problems, the readers of the manuscript will find interplay of barriers quite
238 useful in real time implementation of IoT solutions towards GB issues.

239 Considering the prevailing literature elaborated above, this study aims to address the following
240 two main gaps:

241 (1) Although previous studies have been conducted on the implementation of IoT-based
242 technologies within sustainable buildings, the analysis of potential barriers impeding
243 the adoption of IoTs-based technologies in GB sector has been unexplored. Hence, this
244 study intends to identify and analyze potential barriers to IoT-based technologies in
245 GBs through an extensive literature review and expert interviews.
246 (2) There is a lack of research delving into the intricating relationships that exist among
247 these barriers; thus, this study also aims to address this shortcoming using SNA.

248 Insert Table 2

249 3. RESEARCH METHODOLOGY

250 A mixed method of qualitative and quantitative approaches was used in this study. The
251 steps taken in this study are illustrated in Figure 1. As shown in Figure 1, there were three main
252 stages within the body of the framework, starting with an extensive literature review. This was

253 followed by data collection and data analysis to achieve the specified goals of the research. The
254 following subsections discuss each phase.

255 Insert Figure 1 here

256 **3.1 PHASE I: Identifying Relevant Barriers**

257 **3.1.1. Systematic Review**

258 This stage comprised two steps: a systematic literature review and a structured
259 interview with the relevant experienced experts. To come up with a comprehensive list of
260 barriers to the adoption of IoT-based technologies for GBs, there is a dire need to, first, conduct
261 an extensive review of the extant literature. To this end, an extensive literature review was
262 conducted, as described by Salihu et al. (2022). First, an inclusive combination of relevant
263 keywords i.e., IoT, Green Buildings, Barriers, Technology Adoption, Exploration, Hindrances,
264 Green Features, Advance Technologies, etc., was set out and subsequently used to search
265 prominent databases such as Science direct, Scopus etc. Following this, several exclusion
266 criteria were set not limiting to, studies other than IoT were not considered for barrier
267 identification, sector of study is building sector only, no geographical bound for paper
268 selection, studies with multiple authors were also considered as it will assist in understanding
269 adoption across multiple countries and cultures, not considered very old research studies, all
270 type of articles are considered for review, whether it's review base, full length article or a
271 conference paper. On the basis of these and the snowballing technique as described by Owolabi
272 et al. (2022), 36 relevant papers are shortlisted for review. Afterwards, each paper was
273 scrupulously examined for identifying the relevant barriers. At the end of this stage, twenty-
274 six barriers under seven main clusters were identified.

3.1.2. Structured Interviews

Once the relative body of knowledge was scrutinized, several structured interviews were conducted with several experienced experts. Similar to Mohandes et al. (2022), the primary aim of doing so was to determine reflective barriers that may have been missing in the literature. To this end, four experts with more than ten years of experience in GBs, and who were involved in related projects that used IoT, were individually interviewed using online platforms. The experts in this study included senior engineers, project managers, and academic researchers, each with significant experience in implementing IoT technologies within sustainable construction projects. The individual interviews were conducted using online platforms such as Zoom and Microsoft Teams, selected for their reliability and capability to provide high-quality audio and video communication, ensuring a smooth and effective interview process. During the interview sessions, participants actively explored the challenges hindering the incorporation of IoT technologies in Green Buildings (GBs). Initially, a carefully curated list of predefined barriers to IoT adoption in GBs set the stage for an organized discussion. Participants were not only prompted to elaborate on these predetermined barriers but were also encouraged to contribute additional factors specific to the nuances of Hong Kong. Despite the open invitation for participants to supplement the list with context-specific insights, it is noteworthy that the initial compilation of barriers received consensus. No new barriers emerged during the interviews, indicating that the predefined list comprehensively covered the primary challenges as perceived by participants. This feedback underscores the resilience of the initial barrier categorization, aligning with the experiences and perspectives of stakeholders in IoT adoption within Hong Kong's distinctive landscape. To provide a consolidated overview of the identified barriers, Table 2 has been meticulously crafted. This table serves as a comprehensive reference, encapsulating the multifaceted challenges hindering the widespread adoption of IoT in Green Buildings, particularly within the dynamic context of Hong Kong.

300 Notably, according to prior studies, the minimum required experience for interviewees is
301 typically at least 5 years (Alankarage et al., 2023), while in this study, the experts have over 10
302 years of experience. Furthermore, research in the construction field suggests that interviewing
303 at least three participants is sufficient to achieve credible insights for pilot study or validation
304 stage (Ng et al., 2005). In this study, data saturation was reached after four interviews, as no
305 additional barriers or necessary refinements were identified.

306 **3.2. PHASE II: Data Collection**

307 This phase includes the procedures for selecting respondents and gathering their profile
308 information, developing the questionnaire survey (QS), and conducting the data collection
309 necessary for the subsequent analysis phase.

310 **3.2.1. Demographic of Respondents**

311 To collect reliable and reflective data, a probability sampling technique was employed
312 in this study. In doing so, the following procedures were chronologically followed.

313 (1) For the respondents' selection criteria, since the goal of the study was to uncover the
314 importance of the barriers impeding the adoption of IoT in GBs, the respondents had to
315 have at least one year of related experience (either in research or practice). In other
316 words, they had to have experience in the application/utilization of IoT-based
317 technologies in GBs for at least one year.
318 (2) Following the specification of the requirements for selecting qualified respondents,
319 several sources for the collection of required data were taken into account. Initially,
320 potential experts were identified through professional networks, targeting individuals
321 with substantial experience in IoT applications within green buildings. Direct email
322 invitations were sent to these researchers and practitioners, including a comprehensive
323 overview of the study, its purpose, and the criteria for participation. Additionally, open

calls for participation were posted on professional and academic social media platforms such as ResearchGate, LinkedIn, and Twitter. These posts contained detailed information about the study and clear instructions on how to participate and were strategically shared in relevant groups and forums to reach a targeted audience of qualified experts. Collaboration with relevant organizations, such as the Hong Kong Green Building Council, was also undertaken, requesting them to disseminate the invitation through their networks, including newsletters, email lists, and social media channels. To ensure a comprehensive reach, follow-up reminders were sent to interested participants who had not yet confirmed their participation. Attendance at industry webinars and virtual conferences was also utilized to personally invite experts and discuss the significance of the study. This thorough and diverse approach ensured that a robust and representative pool of qualified respondents was obtained for the study.Figure 2 shows the profiles of respondents who participated in this study. As can be seen, around half of the respondents held UG and M.Sc. degrees, while the remaining half held a PhD degree. Construction management emerged as the most commonly held degree among the respondents. In addition, the majority of the respondents had 3 to 6 years of relevant experience and they were mainly researchers.

Insert Figure 2

3.2.2. Questionnaire Survey (QS) Development

While selecting qualified respondents, the research team made efforts to develop a related questionnaire survey (QS). In doing so, the barriers identified from the literature and experts' interviews were incorporated into the corresponding QS using Google Docs; the barriers were inserted in the rows, while their importance levels were shown in the columns. To complete the designed QS, the respondent had to define the relevance of each barrier in the adoption of IoT within GBs using a Likert scale, as explained in detail by Durdyev et al. (2022).

After developing the related QS, they were sent to 196 qualified respondents (either through online platforms or face-to-face meetings). Of these, 111 filled out the developed QS, showing an acceptable response rate of approximately 56%, as supported by Tabatabaee et al. (2022).

3.3 PHASE III: Network formation and analysis

The primary reason for the application of the network approach in this study is that barriers are a constituent part of a highly interrelated system, in which each barrier has reciprocal influences on other barriers (Fathalizadeh et al., 2021). Similarly, SNA was employed as it can deal with interrelated systems (Pryke, 2012) that are seen as networks (Fathalizadeh et al., 2021).

Networks were constructed using two matrices of nodes and edges. Nodes could be any entity, such as barriers for IoT adoption (see Table 2 for details), and the edges could represent the extent to which barriers are correlated (Horvath, 2011). Spearman's rank correlation coefficient technique was used to calculate the correlation values between barriers, considering its robustness to outliers and the potential to handle non-normal distributions of data (Horvath, 2011). The steps taken to convert qualitative interview data into correlation analysis include:

Step 1. Give each response a number between 1 to 5, using a Likert Scale, in the increasing order of relevancy of each barrier to IoT adoption.

Step 2. Select the appropriate correlation test. Three tests were considered in the present research: 1) Pearson's Correlation Coefficient (PCC) (Sedgwick, 2012), 2) Kendal's Rank Correlation Coefficient (KRCC) (Zhang et al., 2023), and 3) Spearman's Rank Correlation Coefficient (SRCC) (Ali Abd Al-Hameed, 2022). When there is a linear correlation between variables in a dataset (positive or negative), PCC can be used (Li et al., 2022), which was not the case for the analysis in the present study. Then, the selection is between KRCC and SRCC. If there are any tied values in the data, regardless of its percentage, SRCC yields

the near-desired coverage rates, contrary to KRCC whose results are at a much distance, especially when the percentage of ties rises (Puth et al., 2015). Considering the inevitable existence of ties in the dataset, SRCC was finally opted for. SRCC steps include (Song and Park, 2020):

SRCC Step 1. Fill in the columns of (Excel) spreadsheet with pairs of data,

SRCC Step 2. Rank data in columns from 1 to n, with 1 referring to the lowest,

SRCC Step 3. Calculate the ranks' difference of each pair and insert the differences in a column labelled d,

SRCC Step 4. Square d and insert the results in a column labelled d^2,

SRCC Step 5. Calculate Σd^2,

SRCC Step 6. Calculate the standard SRCC formula, and finally

SRCC Step 7. Interpret the result, which ranges from -1 to the maximum of +1. -1 indicates a strong negative correlation, +1 strong positive correlation, and 0 no correlation.

Step 3. Increase the values of the dataset to the power of β to amplify the disparity between strong and weak correlations; here, $\beta = 4$ was used, as recommended by (Hosseini et al., 2020).

Step 4. The correlation matrix, containing entities significant at 0.05, is fed into the network (Fleischer et al., 2022). For this step, a Python package, NetworkX, was used for creating, manipulating, and studying the structure, dynamics, and functions of complex networks.

3.3.1. Centrality metrics

Next, some of the most common centrality metrics were used to explore the relative significance of the barriers. The metrics were degree centrality, closeness centrality, betweenness centrality, eigenvector centrality, harmonic centrality, load centrality, Katz centrality, and communicability betweenness centrality. These measures identify various

important dimensions of an element in a network (Wasserman and Faust, 1994, Hansen et al., 2011). The respective definitions are summarized in Table 3. At the network level, the density was calculated, which defines the proportion of possible lines present in the graph (Newman, 2006).

Insert Table 3

3.3.2. Identifying the most critical centrality metric

The centrality metrics for each barrier were calculated and their values were stored in an Excel worksheet. The resultant is a dataset encompassing 8 columns that equals the number of centrality metrics used in this study, and 26 rows that are on par with the number of barriers. The problem with the dataset is that it cannot provide a basis for prioritizing barriers in the network. This is because each centrality metric ranks barriers differently and no particular metric is recommended. This might lead to misleading outcomes, especially in the absence of previous studies with similar data to define the most critical network measure applicable to the network and data at hand. As argued by (Fathalizadeh et al., 2021), principal component analysis (PCA), a well-known unsupervised dimensionality reduction technique, can be used to solve the problem.

The goal of PCA is to find a lower-dimensional space. The PCA space consists of k principal components, each of which has a different robustness regarding the amount of variance in its direction. The first principal component ($(PC_1 or v_1) \in R^{M\times 1}$) of the PCA space represents the direction of the maximum variance of the data, the second principal component has the second-largest variance, and so on.

Applying PCA to determine the most informative centrality metric was considered acceptable, informed by the approach taken in previous studies on the topic (Ashtiani et al., 2019). This approach is further justified by the application of PCA; scholars could capture

various vital dimensions reflected in different metrics in the first component offered by PCA (Jolliffe, 2002).

3.3. Barriers clusters

Networks typically have modular structures. This implies that a network comprises multiple communities of entities, and most connections are found among entities within the same community. In contrast, connections among communities are weaker and less frequent. The quality of separating a network into several clusters is calculated using a modularity value, which is a scalar value within the range of (−1, 1). This value represents the density of intra-cluster links, as compared to that of inter-clusters, calculated using Eq.1 for weighted networks (Blondel et al., 2008):

$$Q = f(x) = \frac{1}{2}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2_m}\right]\delta(c_i, c_j) \quad (1)$$

where A_{ij} is the weight of the edge between i and j, k_i, which is calculated using Eq. 2 represents the sum of the weights of the edges attached to i, c_i is the community to which i belongs, and δ function $\delta(u, v)$ is 1 if u = v and 0 otherwise. m is calculated using Eq. 3.

$$k_i = \sum_j A_{ij} \quad (2)$$

$$m = \frac{1}{2}\sum_{ij} A_{ij} \quad (3)$$

Additionally, to identify the communities embedded within the network structure, a modularity function was used.

4. RESULTS

4.1 Barriers' centrality values

Figure 3 shows that while barriers 20 (cybersecurity and data risks) and 11 (inadequate green products and tools) are the most and least central barriers according to all metrics, respectively. However, the ranks of the other metrics differ. For example, barrier 14 stands on the second rank of the list, higher than barrier 21, from the perspective of load centrality. However, the reverse is true when considering them from the perspective of communicability betweenness centrality. They both share the same rank according to harmonic centrality. Another example of this disagreement is the comparison between barriers 15 and 24. Barrier 15 is more important than Barrier 24 from the perspective of degree centrality. Barrier 24 is considered more critical than barrier 15 in terms of closeness centrality. This was also the case for the remaining barriers. Here, PCA identifies the most informative centrality metric, based on which barriers can be ranked according to importance.

Insert Figure 3 here

4.2 Ranking the barriers

Table 4 confirms that the first principal component explains most of the variance (9.36E-01), followed by the second principal component showing a variance of 4.06E-02. This implies that PC1 should be maintained, and its values determine the most informative centrality metric. It is evident from observing the PC1 values that communicability betweenness centrality stands out from the crowd (Table 5).

Insert Tables 4 and 5

Table 6 tabulates the normalized values of communicability betweenness centrality in accordance with the relative importance of the barriers. It shows that barrier 20 is the predominant barrier, which has a higher rank than barriers 21, 14, and 24, which rank second,

*third, and fourth, respectively, out of the 26 barriers. At the bottom of Table 6, barrier 11 has the least significance, considering that it is assigned the lowest possible normalized value. Barriers 4, 26, and 12 are the second, third, and fourth least significant barriers, respectively, from the centrality metric perspective.*Insert Table 3

Insert Table 6

4.3 Cluster of barriers

Four clusters were detected in the network (modularity and resolution: 0.208 and 1, respectively) as shown in Figure 4. The density of the graph was 0.415. The hue of the nodes represents the clusters to which each barrier belongs, whereas the size of the nodes is dependent on the relative importance of the barriers in the network (Table 6).

These clusters are primarily responsible for the negative influence of the four constructs, hindering the adoption of IoT-based technologies in GBs. As depicted in Figure 4, the cluster with the most significant number of barriers is shown in light purple. Nine significant barriers belong to this cluster. These include increased process costs, costly tools, gadgets, and software; inadequate green products and tools; energy inefficiency IoT devices; lack of green building technologies database; fewer GB codes/ regulations available; uncertain government policies; absence of government support; lack of awareness; and documentation requirements. These observations indicate the significance and weight of this construct as an underlying problem in the adoption of IoT-based technologies in green buildings. The next cluster in aqua encapsulates seven barriers reflecting high up-front costs, low costs, uncertain costs for IoT-enabled green features, multi-type big data integration problems, persistent computational challenges, questionable reliability of IoT solutions, and concerns regarding the protection of intellectual property. The cluster shown in green comprises seven barriers: the quality of big data, IoT solutions dependent on complex algorithms, standardization problems, cybersecurity

and data risks, privacy concerns, lack of professional expertise, and lack of coordination among stakeholders. The last cluster, with only three barriers, is of moderate importance as it does not contain any barriers with high importance. The barriers in this cluster include a lack of trust in technology, resistance to change, and lack of quality improvement processes.

Modularity is implemented on the network to find clusters of barriers. Technically, it finds nodes (barriers in this context) that are more densely correlated together than others in a network. In other words, barriers in a cluster have dense correlations between one another and sparse connections with barriers of other clusters. Take B22, as an illustration. B22 refers to the privacy concerns barrier. It is in a cluster of seven barriers (green nodes in Figure 4). It has 11 connections, with six of them being between the B22 and B6, B10, B16, B20, B22, B23, and B26 within the same cluster shown in green. It is inferred that the level of interplay between these barriers of cluster green is higher than their interplay with barriers of other clusters.

Insert Figure 4 here

5. DISCUSSION

Identifying the most critical barriers to adopting IoT in sustainable projects can be considered the primary foundation for practical strategies for integrating IoT in sustainable projects (Kluczek et al., 2021). Despite much research in the field of barrier identification for the adoption of green IoT, the starting point and the barriers of importance for finding efficient solutions are still uncertain; therefore, this study aimed to solve this critical question by first identifying the essential barriers using literature review and expert opinions—finding interaction between barriers using SNA and PCA, and finally clustering barriers into different groups. The contribution of this study is prominent as it shows that no single barrier to the implementation of IoT in GBs is completely independent; hence, overcoming some barriers can reduce the overall impact of other related barriers. Finding such dependencies between

barriers and removing the most effective ones can significantly improve the adoption of the IoT in sustainable construction.

According to the results of this study, cyber security and data risks, intellectual property concerns, and privacy issues are the first, second, and seventh top hurdles to adopting IoT in sustainable projects, respectively. All these barriers are related to privacy and security issues, i.e., privacy and security issues are the most critical barriers to adopting green IoT. As the number of IoT devices increases, more data are being generated. This trend would increase the risk of intruders breaching the system, resulting in security concerns and data loss (Malik and Kushwah, 2022). This enhancement also increases the risk of intellectual property concerns because the need to share information with outside parties increases (Briggerman et al., 2012). This is compatible with the results of Maksimovic (2018); the study presented privacy and security as the keys to the successful implementation of IoT applications in GBs. This study also emphasizes the need for security approaches and data privacy for each IoT system in sustainable construction. Wang et al. (2021a) also listed the names of some privacy and security attacks that occur in IoT adoption, namely, phishing attacks, false data injection attacks, and worm and virus attacks, along with potential consequences and possible solutions. Abomhara and Køien (2015) presented many reasons for cyber security threats, including a lack of human presence during the operation of IoT devices and a lack of support for IoT components for complex security schemes. According to Wang et al. (2018), privacy and security issues can be alleviated using advanced technologies, powerful and robust policies, and simpler approaches that can be adopted to implement IoT. The current study also concluded that privacy and security concerns had the strongest relationship with most of the other barriers, which implies that solving these barriers can effectively influence other barriers (Figure 4).

The third and fifth most crucial obstacles to green IoT applications in the construction industry are the lack of good regulations and standardized codes for green projects and the lack

of support from the government, respectively. These barriers were closely related to the government and whether the country is developed. For many developed countries, although there is codes and standards for green buildings, there is still rooms for improvement in integrating these codes with new technologies like IoT. This finding was echoed by Bortone et al. (2022). They emphasized that proper guidelines from the government with policies and strategies are necessary to tackle the main barriers to adopting green projects, including uncertainty in costs, lack of knowledge of the benefits of implementing GBs, lesser interest from the government, and resistance to change. In contrast, for many developing countries, the government still lack a necessity codes and standards for green buildings. In such countries, the lack of necessary codes and standards for sustainable practices can provide a good excuse for many organizations and building owners to avoid adopting green IoT in their practices. The lack of green codes has been highlighted in many countries such as Iran (Fathalizadeh et al., 2021) and Ghana (Ghansah et al., 2021). In addition, the lack of government support is another issue in these countries. According to Fathalizadeh et al. (2021), the government might act as a major hurdle in many developing countries, such as Iran and Ghana, due to widespread corruption that hinders the process of setting proper GB codes. The governments of these countries have indicated that sustainable regulations are unnecessary and expensive.

The fourth barrier is the need to document data results from green IoT. This barrier is closely related to management. Good documentation by organizations and building owners can significantly eliminate the possibility of data loss and errors during the transition to different IoT devices and the sharing of information with other systems. Additionally, good documentation practices can save time, cost, and energy and enable the tracking of relevant information in due time in sustainable projects (Ismail, 2020, Zuo et al., 2017). This is consistent with the study by Djedjig et al. (2017); the study emphasized that low-quality documentation is a critical barrier to effective GB maintenance management in construction projects. According

563 to Zhang et al. (2017), lesser documentation can hinder updated information among all
564 stakeholders in sustainable projects, making it challenging to resolve potential problems in
565 time. Good documentation can also improve privacy and security. Abomhara and Køien (2015)
566 emphasized the importance of good documentation of all possible threats to IoT devices, which
567 can give us a full understanding of the types of threats and the goals of attackers, helping us
568 take additional measures against these attacks.

569 Other barriers are associated with both organizations and technology. Lower-quality
570 systems for implementing green IoT can result in repetitive computational issues and increase
571 errors during implementation. According to Lawal and Rafsanjani (2021), using smaller and low-
572 quality devices in green IoT can result in serving vast amounts of energy, while the primary
573 goal of IoT is to save energy. Another significant barrier is insufficient funds, which means
574 that organizations might also suffer from inadequate financial issues when implementing green
575 IoT. This is also reflected in the study by Yeon et al. (2018), who suggest providing low-interest
576 government loans for such companies to encourage more companies toward green
577 construction.

578 The present study proved that adoption barriers of IoT are sometimes inseparably
579 interconnected. As Figure 4 depicts, there is no single barrier unrelated to the network (the
580 nodes with no edges to the network). This clearly shows that no barrier listed in this study
581 should be seen as secluded, otherwise localized relief would be obtained. Therefore, addressing
582 the barriers in isolation and without their interplay would provide intangible benefits. The
583 novelty of this study lies in addressing this dilemma by combining the 26 most significant
584 barriers using SNA to offer a more controllable set of four barrier clusters.

6. IMPLICATIONS

The findings of this study have several theoretical and managerial implications. Given the theoretical implications, this research not only identified the critical barriers to integrating IoT in GB projects but also explored and examined the complex interdependencies between identified barriers, clustering them, and prioritizing each cluster according to their level of importance. According to such a structural model which combines qualitative and quantitative methods in the meantime, the criticality of the barriers was examined through SNA modelling. Such modellings aid researchers, through application of this model to their corresponding fields, to first rank the barriers and then adopt proper and timely resolutions in their investigation. What is more, the barriers listed here and the relationship among them can shed light on model conceptualization, especially, when the structure of components and their correlation are all network-based. Furthermore, they show how to externally validate the findings of a study following the procedures described in this research.

In addition to the theoretical implications mentioned above, this study's findings provide some managerial insights.

First, significant hinderers slowing the adoption of IoT-based technologies in GBs have been identified and categorized. This categorization could hint projects' managers to figure out which barriers are highly-frequented in a given category and their relative importance. This insight matters especially when wise and proper budgeting is needed for integration of IoT technologies into GBs. Take Security and data risks as well as regulation related barriers, as an illustration. While they are considered to be the most critical impediments, organizational and technology-based barriers are of much less criticality. In the meantime, the respective managers would be able to prioritize the barriers and prepare the necessary arrangements regarding project specifications.

609 Second, the relationship and their viability or importance, as a, respectively, link and the weight
610 from the outlook of SNA, discernibly demonstrate how a barrier influences and interacts with
611 others and how much important this effect might be in practice.

612 Third, it also gives a reasonably good understanding of the hierarchical structure of a barrier,
613 considered as node in SNA, regarding how many weighted connections it has with others in
614 the network of barriers at large. This would ease dedicating the required resources to overcome
615 a barrier.

616 Fourth, the findings of the network analysis would facilitate more optimal stakeholders'
617 engagement. Various stakeholders are assigned to address specific barriers, while considering
618 the undisputed interrelationships among barriers and their inference with other domains. This
619 is doable only when constructive collaborations take place.

620 Fifth, the data-driven method applied in the present work and its analysis can ease monitoring
621 and evaluating the efficiency and success of the initiatives taken to mitigate or, hopefully,
622 eliminate the barriers to IoT adoption.

623 **7. LIMITATIONS AND FUTURE WORKS**

624 Despite the contributions made to the body of relevant knowledge, this study has
625 several limitations that should be noted in future research. First, investigating the main barriers
626 to the of adoption IoT technologies in GBs is heavily reliant on the location of study and the
627 results of the main barriers can be introduced differently based on the geography of the analysis.
628 In this regard, the current study takes the aid of experts with rich experience in Hong Kong;
629 hence, the findings cannot be generalized to other contexts. To take note of this limitation,
630 further studies need to be conducted in other regions, and accordingly, the findings can be
631 compared with those of this research. By way of illustration, as mentioned in discussion

632 sections, governmental hurdles are considered the main barriers in developing countries such
633 as Iran due to the widely corrupted system in these kinds of countries (Fathalizadeh et al., 2021)
634 while in Hong Kong, data risks and cyber security issues are considered the major barriers for
635 adoption IoT based technologies in GBs. Second, even though the relationships among the
636 barriers to implementing IoT within green buildings have been determined in this study, the
637 causal relationships — that is, the cause-and-effect relationships between the barriers — need
638 further investigation. Thirdly, it is imperative to deal with the uncertainty associated with the
639 qualitative data collected on the importance of barriers identified in this research; thus, future
640 researchers might consider using fuzzy set theory in the concerned theme. Fourthly, this study
641 utilizes a quantitative-based methodology to unravel the relationships among the related
642 barriers; thus, future research needs to exploit a qualitative methodology to undertake a more
643 in-depth critical analysis of the themes extracted from interviews. Finally, the analysis did not
644 consider the respondents' years of experience and their specific fields of study; hence, future
645 research should address these factors and make comparisons to generate new insights.

646 **8. CONCLUSIONS**

647 Although the adoption of IoT has recently attracted the attention of researchers and
648 practitioners in the construction sector, the current body of knowledge is deprived of a study
649 examining the barriers to IoT-based technologies in GBs. To fill this gap, this study
650 investigated the relationships among the barriers impeding the adoption of IoT-based
651 technologies within GBs using SNA. Based on the data collected from experienced experts in
652 the Hong Kong building and construction sector, the following conclusions can be drawn:

653 (1) Twenty-six barriers impede the adoption of IoT within the concerned sectors. These
654 barriers can be categorized into seven clusters.

(2) The most significant barriers belong to the "political/regulatory" and "security" categories, constituting the highest number of critical barriers as compared to the other clusters.

(3) It is observed that "cybersecurity and data risks," "concerns over the protection of intellectual property," "fewer GB Codes/regulations available," "documentation requirements," and "uncertain government policies and absence of government support" are the most critical impediments to the adoption of IoT-based technologies within sustainable buildings.

The observations produced in this research can assist managers and policymakers in identifying critical barriers to IoT-based technologies implementation in sustainable buildings by aiding the decision-making process. Furthermore, this study promotes awareness, bridges the gap between theory and practice for the successful adoption of sustainable construction in GB, and generates further debate (essential for achieving the sustainability goals of GBs).

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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907 **Table 1.** Summary of the relevant literature reviewed

SNo	Title	Keywords	Journal	Country	Institution	Citation	Research Methodology	Key Research Findings	Research Recommendations
1	Designing a legal framework of green environment in smart home project.	Designing, Green Environment, Smart Home, Legal Framework, Sustainable	International Journal of Supply Chain Management	Malaysia	Universiti Utara Malaysia	Yeon et al. (2018)	Mixed method: Legal doctrinal research and qualitative research.	-Highlighted amendments to the law and policy in ensuring the success of the smart home project and preservation of green environment.	-Government of Malaysia to recognize the environmental potential of smart features.
2	Greening the future: Green Internet of Things (G-IoT) as a key technological enabler of sustainable development.	Green Internet of Things (G-IoT), Green economy, Health, Environment, Sustainable development	Internet of things and big data analytics toward next-generation intelligence	Bosnia	University of East Sarajevo	Maksimovic (2018)	Critical Review	-Presented the analysis of the significance of green technologies' processes in sustainable development.	-It is recommended to explore G-IoT, which holds the potential to transform and bring numerous benefits.
3	ND BIM-integrated knowledge-based building management: Inspecting post-construction energy efficiency.	Building information modeling, Building management system, Post-construction lifecycle, Energy efficiency, N dimensional implementations	Automation in Construction	New Zealand	Auckland University of Technology	GhaffarianHoseini et al. (2019)	Simulation Modeling	-Proposed system is expected to provide simulation-based supervisory control, while automatically detecting and diagnosing operational faults.	-It is recommended to implement the developed framework to more real-world projects.
4	Visualize GIS, BIM and IoT data for comgprehensive green building parameters monitoring.	BIM, GIS, IoT, Green Building, Indoor Air Quality	The 8th International Conference on Innovative Production and Construction	Hong Kong SAR	University of Hong Kong	Yin et al. (2019)	Modeling and Case Study	-Presents a novel approach integrating GIS, BIM and IoT data for visualizing Indoor Environment Quality (IEQ) parameters and ameliorating the decision-making process during asset operational phase.	-To develop a holistic platform with feasible system architecture, functions and user interface for practical usage of a green building project.
5	Improving maintenance management practices on green building projects.	Framework, ICT, Project, Maintenance management, Green building, Improper maintenance	Management of Environmental Quality: An International Journal.	Malaysia	Universiti Malaysia Perlis	Ismail (2020)	Conceptual Framework Development	-Develop a new Information and Communication Technology (ICT) based approach for managing maintenance in GB schemes.	-The findings reveal the need for more sophisticated maintenance management solutions that accord with the needs of GB schemes to manage quality and reduce associated defects.
6	Application of Lifecycle Measures for an Integrated Method of Environmental Sustainability Assessment of Radio Frequency Identification and Wireless Sensor Networks.	lifecycle indicators; sustainability; technology assessment; radio frequency identification; wireless sensor networks	Energies	Poland	Warsaw University of Technology	Kluczek et al. (2021)	Life Cycle Analysis	-A new environmental sustainability assessment method is developed to assess radio frequency identification (RFID) and wireless sensors networks (WSN).	-It is recommended to have different life cycle scenarios for analysis.
7	A topical network based analysis and visualization of global research trends on green building from 1990 to 2020.	Green building, Topic evolution, Text mining, Latent dirichlet allocation, Community network analysis, Literature review	Journal of Cleaner Production	China	Shenzhen University	Wu et al. (2021)	Text Mining Techniques (latent Dirichlet allocation (LDA) modeling, Word2vec, and community network analysis)	-Presents a text mining based method to identify the key research topics and trends from the existing abundant GB research.	- In the future, scholars could combine this method with bibliometric analysis to quantitatively review the massive literature more thoroughly. Also, it is advised to exercise expertise and carefulness during the data cleaning process.
8	Trends, benefits, risks, and challenges of IoT implementation in residential and commercial buildings.	Internet of things, Residential buildings, Commercial buildings Smart buildings, Review	Energy and Built Environment.	USA	University of Georgia	Lawal and Rafsanjani (2021)	Critical Review	- A review of IoT approaches in residential and commercial buildings is provided. -Integration of various IoT technologies with different capabilities, data storage and processing, and privacy and security risks are identified as the main challenges for IoT implementation.	- Future research is needed to fully embrace Cloud services and new ways of connectivity in order to get the full benefits of the IoT technology.
9	Gaps in Regulation and Policies on the Application of Green Technologies at Household Level in the United Kingdom.	Green technologies; Green Industrial revolution; GHG emissions; UK Building sector; Environmental awareness	Sustainability	UK	Cranfield University	Bortone et al. (2022)	Critical Review	-This study provides an overview and analysis of the existing regulation and standards in the UK building/household sector, to understand the current state-of-the-art and identify gaps preventing Green-Tech wider implementation and use.	--Complete and clear guidelines addressing environmental awareness, the performance and economical convenience of Green-Tech implementation and related regulations, are required to come to a consensus on the best way to move forward to achieve sustainability and NET-ZERO targets.

10	Artificial intelligence in green building.	Artificial intelligence, Green building, Bibliometric analysis, Systematic analysis, Sustainability	Automation in Construction	Hong Kong	The Hong Kong Polytechnic University	Debrah et al. (2022)	Mixed-methods systematic review	- The study aims to reveal the synthesis between AI and GB, as well as to highlight research trends along with knowledge gaps that may be tackled in future AI-in-GB research.	- It is recommended to conduct, future research in directions of AI-in-GB as follows: digital twins and AI of things; block chain; robotics and 4D printing; and legal, ethical, and moral responsibilities of AI-in-GB.
11	A Survey on Next Generation IoT Networks from Green IoT Perspective.	Internet of Things · Green IoT · Wireless sensor network · IoT challenges · IPv6 · M2M · Smart connectivity	International Journal of Wireless Information Networks.	India	Jaypee Institute of Information Technology	Malik and Kushwah (2022)	Literature Survey	- A detailed study on several prevalent and innovative IoT solutions in terms of Green IoT is performed. More specifically, the assessment and comparison of these Green IoT solutions are carried out based on their characteristics, technology used, outcomes, usability, and their limitations.	-Furthermore, the actual impact of Green IoT on the environment and economy would be of importance; therefore, more research to achieve Green IoT is required.
12	Development of an IoT assessment method: An interdisciplinary framework for energy efficient buildings.	Sustainable rating systems, Energy efficient, Building technologies, Intelligent buildings, Internet of Things (IoT)	Energy and Buildings	Egypt	Ain Shams University	Metwally et al. (2022)	Assessment Model and Case study	-This study proposes a criteria framework to develop a simplified method, to assess IoT implementation level and the impact of IoT applications in buildings. This framework method is based on 3 main domains: input (embedded parameters), throughput (controlled variables), and outcome (impact) domains.	-This framework could be further developed by experts within the IoT scope to an IoT rating system for architectural buildings and practically validated for such buildings.
13	Building information modelling and green building certification systems: A systematic literature review and gap spotting.	Building information modelling, Green building certification system, Systematic literature review Sustainability	Sustainable Cities and Society	New Zealand	Victoria University of Wellington	Olanrewaju et al. (2022)	Systematic literature review (SLR) and Gap spotting	-This paper explores the synergies between BIM and GBCS to achieve a deeper understanding of the GBCS currently BIM-enabled, level of BIM implementation in GBCS sustainability areas, challenges and gaps in integrating BIM and GBCS, BIM and GB tools currently in use and areas for further research in the BIM-GBCS domain.	-It is recommended that future studies should critically evaluate the tools identified in this study to ascertain their level of contribution to building life cycle sustainability assessment across the building lifecycle.
14	Representations of the Smart Green Concept and the Intention to Implement IoT in Romanian Real Estate Development	Sustainability; green building knowledge; operating cost factors; IoT implementation intentions; real estate developers; mediation analysis	Sustainability	Romania	Aurel Vlaicu University of Arad,	Cuc et al. (2023)	Survey Analysis	- The aim of this research is to analyze whether familiarity with the smart green concept influences the decision to implement the IoT on a large scale at the organizational level through the perception of specific determining factors in choosing the development of green building projects considering the operational costs.	- Further research should assess real estate developers' satisfaction with large investment in IoT strategy for green building development, in order to further depict hindering factors of future smart city development.
15	Digital Twins for Intelligent Green Buildings	Intelligent Green Building; Digital Twins; smart city; information interaction; real-time visualization	Buildings	China	Tianjin Chengjian University	Yang et al. (2022)	Critical Review	-This study aims to analyze the digital development of smart green buildings to make it easier to create contiguous ecological development areas in green ecological cities.	- It is needed to improve its intelligent control system for its interior environment. And undertake study on this subject and perform an in-depth analysis of relevant technologies for creating IGB in future research.

909 **Table 2.** Barriers hampering the adoption of IoT in GBs

Category	Barriers	Definitions	Citations
Financial	1. High Upfront Costs	In contrast to conventional construction, incorporating IoT-enabled green features results in high upfront cost, which creates hindrances towards its effective implementation.	Feng et al. (2019); Onososen et al. (2019); Raouf and Al-Ghamdi (2019); Coulby et al. (2021); Wang et al. (2021b); Wu et al. (2021); Bortone et al. (2022); Malik and Kushwah (2022); Olanrewaju et al. (2022); Olawumi and Chan (2022)
	2. Insufficient Funds	Despite the existing maturity level of green building practices, it still needs additional investments from governments to overcome problems like insufficient funds or constrained budgets, for effective implementation of IoT-enabled green solutions.	
	3. Increased Process Costs	In addition to the high upfront costs, IoT-enabled green features for green building incur higher operating costs, thus resulting in increased process costs.	
	4. Uncertain Costs for IoT-enabled Green Features	The green-construction industry is evolving with several IoT-enabled innovative green features being developed gradually to provide sustainable solutions. Therefore, sometimes, the costs become uncertain due to these unique features.	
	5. Costly Tools, Gadgets, and Software	Generally, green building tools, gadgets, and related software, such as energy simulation software, are high in cost. Consequently, enabling IoT with these technological tools and gadgets results in increased costs.	
Technical	6. Quality of Big Data	Since IoT-enabled devices produce large amounts of data, i.e., big data, it requires thorough data curation processes prior to its usage.	Maksimovic (2018); Wang et al. (2018); GhaffarianHoseini et al. (2019); Parkinson et al. (2019); Raouf and Al-Ghamdi (2019); Yin et al. (2019); Bibri and Krogstie (2020); Ismail (2020); Jin et al. (2020); Abusukhon (2021); Alsharif et al. (2021); Kluczek et al. (2021); Lawal and Rafsanjani (2021); Metwally et al. (2022); Olawumi and Chan (2022)
	7. Multi-Type Big Data Integration Problems	One of the main problems with multi-type big data lies within its integration or interoperability, i.e., connectivity issues from different devices to produce the desired results.	
	8. Persistent Computational Challenges	Since the analysis of big data requires high end computing machines, it results in persistent computational challenges around storage, analysis, and visualization of big data.	
	9. Questionable Reliability of IoT solutions	Undoubtedly, IoT-based solutions are contributing to various potential applications; however, their reliability is a key criterion for effective implementation.	
	10. IoT Solutions are dependent on Complex Algorithms.	Many IoT-enabled solutions require complex computational tools that are based on complex algorithms, therefore understanding is crucial for effective implementation of such IoT solutions.	
Environmental	11. Inadequate Green Products & Tools	As it is an evolving field of studies, over time, various innovative techniques are being used in the practice, which requires continuous improvements in terms of energy efficiency.	Onososen et al. (2019); Malik and Kushwah (2022)
	12. Energy Inefficiency of IoT Devices	Green building focuses on the reduction of energy consumption; however, the use of IoT devices consumes excessive energy, which mandates proper considerations for energy design optimizations.	

	13. Lack of Database of Green Building Technologies	As compared to the modern-day challenges of GB construction and IoT implementation, there exist clear shortcomings in the adequacy of scientific databases.	
Political / Regulatory	14. Fewer GB Codes / Regulations Available	Despite the great potential for environmental improvements, there exist fewer GB Codes / Regulations options available to date.	Yeon et al. (2018); Onososen et al. (2019); Ismail (2020); Lie et al. (2022); Bortone et al. (2022); Malik and Kushwah (2022)
	15. Uncertain Government's Policies and Absence of Government Support.	A few countries have clear governmental policies on the adoption of green features; however, many countries still lack clear governmental policies and support for effective implementation.	
	16. Standardization Problems	As it is an emerging field of study, not enough examples to create standards for IoT adoption in GBs are in place, thus indicating standardization problems.	
Social	17. Lack of Awareness	Awareness is the key to effective implementation of technology-based solutions and its absence creates major problems. Workers do not show interest in gaining awareness about the potential benefits of IoT-based solutions.	Feng et al. (2019); Onososen et al. (2019); Abusukhon (2021);Wang et al. (2021b); Bortone et al. (2022)
	18. Lack of Trust in the Technology	One of the main challenges in technology adoption lies within the lack of trust in the technology. It is mainly due to workers not showing interest in knowing the potential benefits.	
	19. Resistance to Change	Change is always demanded in nature, but individuals tend to stick to industry norms and their own best practices, and resist any change towards the betterment, i.e., resist the adoption of IoT-enabled solutions.	
Security	20. Cybersecurity and Data Risks	As IoT devices generate plenty of data, it creates risks of data manipulation, and theft, thus creating cybersecurity risks.	Maksimovic (2018); Wang et al. (2018); Bibri and Krogstie (2020); Wang et al. (2021b); Debrah et al. (2022); Malik and Kushwah (2022)
	21. Concerns over Protection of Intellectual Property	IoT-enabled solutions are generally protected for intellectual property, and individuals have concerns over the protection of these patented solutions.	
	22. Privacy Concerns	IoT-generated big data results from certain applications lead to the identification of the users and make the process transparent; however, at the same time, this creates privacy concerns among the stakeholders.	
Managerial	23. Lack of Professional Expertise	IoT-enabled green building solutions require a unique and extensive skill set, instead of the typical construction skillset, which is predominantly lacking in the masses.	Raouf and Al-Ghamdi (2019); Ismail (2020); Cielo and Subiantoro (2021); Wang et al. (2021b); Wu et al. (2021); Olawumi and Chan (2022); Olanrewaju et al. (2022)
	24. Documentation Requirements	As compared to typical construction, where the documentation requirements are well established, this field lacks detailed documentation.	
	25. Lack of Quality Improvement Processes	Owing to the lack of professional expertise and detailed documentation, the quality achievement is questionable, and therefore, its improvement becomes unclear.	

	26. Lack of Coordination among Stakeholders	Coordination among stakeholders is crucial in achieving desired project objectives. As this field is not matured, there exists coordination issues amount the stakeholders.	

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912 **Table 3.** Summary of relevant theory and concepts useful for barriers analysis

Social network construct	Reference(s)	Relevance to barriers
Degree centrality	(Wasserman and Faust, 1994)	The degree of a barrier is simply the number of other barriers connected directly to the barrier.
Closeness centrality	(Wasserman and Faust, 1994)	This measure focuses on how close a barrier is to all the other barriers in the set of barriers. The idea is that a barrier is central if it can quickly interact with all others.
Betweenness centrality	(Wasserman and Faust, 1994)	It measures the distance of a barrier from other barriers through the shortest paths. It is an essential indicator of barriers with a major influence and control over the communication flow.
Eigenvector centrality	(Wasserman and Faust, 1994)	It is a more sophisticated view of centrality: a barrier with few connections could have a very high eigenvector centrality if those few barriers were very well-connected with others.
Harmonic centrality	(Kharysh, 2019)	The harmonic centrality of a barrier is the sum of the reciprocal of the shortest path distances from all other barriers.
Load centrality	(Newman, 2001, Goh et al., 2001)	The load centrality of a barrier is the fraction of all shortest paths that pass through that barrier.
Katz centrality	(Katz, 1953)	Katz's centrality computes the centrality for a barrier based on the centrality of its neighbors. It is a generalization of the eigenvector centrality.
Communicability Betweenness Centrality	(Estrada et al., 2009)	The communicability betweenness measure uses the number of walks connecting every pair of barriers as the basis of a betweenness centrality measure.

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914 **Table 4.** Amount of variance each PC explains

PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
9.36E-01	4.06E-02	1.94E-02	1.89E-03	1.10E-03	5.21E-04	1.34E-04	3.29E-06

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916 **Table 5.** Most important feature (centrality metric) from PC1

Betweenness Centrality	Load Centrality	Eigenvector Centrality	Closeness Centrality	Harmonic Centrality	Communicability Betweenness Centrality	Katz Centrality	Degree Centrality

3.68E-01	3.68E-01	3.70E-01	3.64E-01	3.79E-01	4.00E-01	3.69E-01	1.45E-01

Table 6. Normalized values of communicability betweenness centrality and the relative importance of the barriers

Ranking	Barriers	Communicability Betweenness Centrality
1	Barrier 20	1
2	Barrier 21	0.749692385
3	Barrier 14	0.738794566
4	Barrier 24	0.583416072
5	Barrier 15	0.553102281
6	Barrier 8	0.552216096
7	Barrier 22	0.516622077
8	Barrier 13	0.516606315
9	Barrier 2	0.51293135
10	Barrier 5	0.511360653
11	Barrier 16	0.501192684
12	Barrier 7	0.446983729
13	Barrier 25	0.415571761
14	Barrier 18	0.380386021
15	Barrier 19	0.361017933
16	Barrier 17	0.353563068
17	Barrier 23	0.351738401
18	Barrier 3	0.246329725
19	Barrier 10	0.237218363
20	Barrier 6	0.234244707
21	Barrier 9	0.203912555
22	Barrier 1	0.199584649
23	Barrier 12	0.188665496
24	Barrier 26	0.105996059
25	Barrier 4	0.054500535
26	Barrier 11	0

Figure 1. Research Methodology

Figure 2. Demographics of respondents based on their: (a) qualification, (b) degree, (c) experience, and (d) profession

Figure 3. Centrality metrics and their values

925 **Figure 4.** The network of the barriers and the respective clusters, with B20 – Cybersecurity
926 risks having the highest betweenness centrality.