BIM-Based Search and Selection of Construction Material Suppliers: A dedicated framework and prototype

Purpose

This study addresses the key issues concerning supplier selection in traditional construction procurement by proposing an innovative, novel, state-of-the-art prototype plugin (BIM-SSR) and an associated conceptual framework. It enhances Building Information Modelling (BIM) capabilities through web crawling and analytical hierarchy processes (AHP). It utilizes the World Wide Web (WWW) to procure construction material suppliers.

Design/methodology/approach

Prevalent issues in traditional procurement of material suppliers have been identified through a rigorous literature review. Field experts vetted these issues. A framework has been presented to address these issues based on integrated web crawling and AHP as a multi-criteria decision-making (MCDM) method. A BIM prototype (BIM-SSR) has been developed using Python and plugged into Autodesk Revit to automate the search and evaluation of material suppliers based on precise material specifications from the BIM design. The BIM-SSR prototype is tested through a case study and validated by field professionals for its efficiency in tackling the identified issues.

Findings

Thirteen key issues have been identified concerning traditional construction procurement pertinent to supplier selection. Best-value (BV) procurement was encouraged by identifying supplier selection criteria such as *cost, delivery time, experience, compliance with quality management standards, warranties, and claim period*. The presented BIM-SSR prototype has an efficiency of 80-95% in addressing the issues identified in this study and 97.5% effectiveness in improving the overall procurement management process.

Originality/value

The BIM-SSR prototype developed in this study is a novel and innovative addition to the body of knowledge that has been integrated into Autodesk Revit as a Plugin. Automation of supplier search and selection through digital technologies, including web crawling and integration of traditionally accepted MCDM methods such as AHP in BIM, is another innovation in the current study. Overall, this study presents a holistic, innovative system, from conceptual design to practical implementation and demonstration. This is one of the steps to help the traditional construction procurement process evolve into a more modern and digital procurement.

Keywords: Building Information Modelling (BIM); BIM-SSR; Construction Procurement; Supplier Selection; Web Crawling; Best-value Procurement.

1 Introduction

Construction projects aim to deliver high-quality work within a specified time and budget. However, the delayed supply of materials causes interruptions in project completion and increases the costs, thus hindering the objectives of timely and under-budget completion (RezaHoseini et al., 2021). Supplier selection is a complicated process encompassing numerous interrelated factors to assess the available alternatives (Kumar et al., 2018). Traditionally, contractors solicit suppliers using their contacts or requests for quotations (RFQs) (Choudhry et al., 2012). The search for suppliers is followed by evaluating suppliers based on best-value (BV) criteria such as total cost, quality standards, delivery, etc. (Lam et al., 2010; Safa et al., 2015). However, this approach is slow, tedious, time-consuming, prone to errors, expensive, and inefficient (Akenroye et al., 2019). Further, it may lead to time and cost overruns, wastage of project resources, lower profit margins for project stakeholders, lack of transparency, and poor security and management of stakeholders' information (Bao et al., 2019) that can jeopardize the success of otherwise well-planned projects.

Various approaches have been applied to overcome the challenges of traditional and manual methods for construction materials' supplier search and selection. These include multi-criteria decision-making (MCDM) methods (Tan et al., 2021), best-worst method (BWM) (Singh et al., 2023), bi-level programming model (Zhu et al., 2022), and other intelligent decision techniques (IDTs) (Liao et al., 2022). These methods only cover supplier selection, and the integration of innovative digital supplier search methods in the construction industry is still open to exploration.

Globally, search engines use web crawling algorithms to go through huge amounts of online content, break it down, index it, and make it comprehensible and accessible to users (Desai et al., 2017). Web crawling technology has been used in construction research to collect information on building materials from online research papers and articles and extract a large amount of textual data from various sources (Saeed et al., 2020; Zhang et al., 2021). However, these studies do not incorporate construction material supplier searches based on accurate information from a project repository. Further, the open web is not utilized in pertinent studies, missing out on valuable opportunities to leverage advanced technologies.

Supplier selection is based on multiple variables and criteria; thus, a potential case of application of multi-criteria decision-making (MCDM) methods is evident. MCDM is based on calculating the weightage of multiple alternatives through score-to-rank criteria. Various

MCDM techniques have been reported in the pertinent literature, such as cluster analysis, Analytical Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and others (Tan et al., 2021). Out of these methods, AHP is an MCDM method widely utilized by experts and users due to its flexibility and consistency of results (Ishizaka & Siraj, 2018). Moreover, there is scattered literature on BV procurement of construction suppliers for selecting vendors that consider factors beyond price, such as quality, reliability, compliance, communication, and expertise (Madushika et al., 2020; Ying et al., 2022). Therefore, it is essential that the literature is further explored, and the criteria verified by the industry experts to incorporate the BV procurement of material suppliers to fill this knowledge gap.

Building Information Modelling (BIM) has revolutionized the operations of the construction industry. It is a widely accepted construction management tool, with its implementation encouraged on a public level in many countries (Jiang et al., 2022; Y. Wang et al., 2019). BIM is a rich information platform that contains the complete material information needed for the procurement process and supports customized automation of various management processes. Tan et al.(2021) reviewed the integration of BIM and MCDM methods. The authors summarized the application domains of MCDM with BIM. A review of the literature highlighted only four articles that address the selection of material suppliers using MCDM with BIM, indicating a dearth of literature in this domain. These articles target environmental and sustainable alternative selection (Ahmadian Fard Fini et al., 2017), supplier selection based on their BIM delivery (Mahamadu et al., 2015), resilience capabilities (T. K. Wang et al., 2017), and supplier selection at the prefabrication stage (L. Zhao et al., 2019). While these articles address the use of BIM for material specifications, BIM is not leveraged for its collaborative and automating expertise for research and industrial innovation in supplier selection. The studied articles also lack a framework for BIM-based supplier search.

Overall, there is limited research on developing a unified framework for holistic search and selection of construction material suppliers using integrated BIM-MCDM. Accordingly, the current research addresses this gap by introducing an integrated material search and selection prototype. This study is a novel approach and has two-fold novelty. First, this is a pioneering study that leverages BIM as a search engine by utilizing the web crawling technique. Adding the web crawling capability to the BIM platform enables it to directly query the web to attain details of potential online suppliers. Second, the current study merges BV procurement using industry-approved supplier selection criteria through an automated MCDM framework that has not been reported by others so far. Leveraging BIM as a procurement tool for construction stakeholders will bring much-needed innovations in traditional procurement processes that are in line with the technological advancements pushed forward by Industry 4.0 and 5.0 endeavours.

The applicability and validation of the research are achieved by addressing the shortcomings of traditional material supplier procurement practices on construction sites. The issues-resolving capability of the presented framework validates the applicability of the research framework using a prototype plugin. The objectives of this study are:

1. To identify the issues in traditional construction supplier selection,
2. To present a dedicated framework and develop a BIM-based prototype to automate supplier search and selection,
3. To validate the developed framework and prototype using a case study and inputs from industry experts.

Aligning with the stated objectives, following research questions have been devised to guide the study. These questions systematically explore the challenges in the traditional construction material supplier selection and provide a BIM-based approach to address them. While addressing these questions, the current study presents a framework to enhance supplier procurement practices in the construction industry. The research questions are as follows:

1. What are the challenges and limitations of the current practices of construction material supplier search and selection?
2. How can a BIM-based framework resolve the identified challenges?

2 Literature review

2.1 Key issues in construction procurement

Selecting contractors, subcontractors, and material suppliers in a construction project is a critical decision with the potential for errors and mistakes. Studies demonstrate that current procurement practices are costly and time-consuming due to tedious and tiresome manual work related to finding, shortlisting, approaching, negotiating with, and selecting the most suitable supplier or contractor (Akenroye et al., 2019). Similarly, due to planning carelessness, clashes, oversights, errors, and irregularities in critical documents, project data may not be communicated effectively, leading to poor quality or non-compliant work (Ogunsanya et al., 2019). Moreover, the quality of construction work may be compromised due to the communication barriers between the stakeholders (Rajeev & Kasun, 2015). Corruption is also common due to subjective and manual decision-making, especially in developing countries (Bao et al., 2019).

The key issues and drawbacks of traditional procurement practices, as demonstrated by the above relevant studies, can be listed as follows:

1) Ineffective data sharing and communication and poor collaboration among the project stakeholders.
2) Expensive procurement processes involving manual calculations, data entry, evaluation, and approvals.
3) Errors and mistakes in manual calculations and estimations.
4) Time wastage and delays due to manual and inefficient methods.
5) Procuring services and materials which do not comply with legal and technical standards of project specifications.
6) The selection of incompetent suppliers due to poor selection techniques adopted by the project team.
7) Corrupt and non-transparent practices by the project stakeholders.
8) Improper change management systems.

2.2 Internet-based supplier search and web crawling

The Internet is extensively used for communication in worldwide businesses. In construction material procurement, internet usage can save up to 60% of the client's time (Yang et al., 2020). Material search has become easy with the introduction of online marketplaces and virtual catalogues, where finding a product and recommending alternative products have been streamlined (Mehrbod et al., 2018). Search engines can leverage web crawling algorithms to go through huge amounts of online content, break it down, index it, and make it comprehensible and accessible to users (Desai et al., 2017). The crawler duplicates and saves the information as it goes and scraps the sites. The documents are typically put away to be seen, translated, and explored like the live web.

Web-based markets can be efficiently explored for enhanced supplier search (Ameri & McArthur, 2011). In the pertinent study, the authors devised an intelligent algorithm for searching suppliers online using Manufacturing Service Description Language (MSDL) that matches and shortlists suppliers based on similarities between the online brochure and the input search query. D'Haen et al. (2016) presented a framework for online supplier search using web crawling, concluding that web-crawled data is more reliable and complete than traditional approaches. Recently, web crawling has been utilized to suggest and shortlist the best online material (Saeed et al., 2020). The pertinent study utilizes an online framework for query-based search for the best deals gathered from online portals using web crawling. However, only a few studies have demonstrated using web crawling techniques in the construction industry. For example, Hwang et al. (2022) have developed a high-quality training image database for construction site monitoring using automated image collection through web crawling. Millions of construction site images are easily collected to form a database. Useful keywords and search strings are essential to the web crawler. They enable the keywords-based searched images to be downloaded. Recently, Kim et al. (2024) utilized a web crawling technique to develop image-based training datasets of construction works and heavy equipment. Further, web crawling has been utilized by Hong et al. (2019) to collect information on building materials from research papers and the Internet. The authors developed an automated database with a continuous updating system, minimizing data collection time and eliminating human errors. Baek et al. (2021) identified various text-based information collection or text-mining techniques for extracting critical information from contract documents in the construction industry. These studies have demonstrated the successful use of web crawling, justifying the possibility of using this technique in various construction processes. However, web crawling has not been used to source construction suppliers from online sources, presenting a gap targeted in this study.

2.3 Supplier selection using MCDM

Supplier evaluation and selection is a complicated procedure involving various critical factors for assessing available alternatives, making it a classic MCDM problem (Schramm et al., 2020). Various MCDM methods have been reported in the literature for evaluating and ranking alternatives for supplier selection (Taherdoost & Brard, 2019).

AHP has been used to rank suppliers based on predefined selection criteria found in the literature that were subsequently weighed by industry experts (Zhao et al., 2019). Triangular Fuzzy Numbers (TFN) and Principal Component Analysis (PCA) have been used to quantify the subjective judgment of industry experts on supplier selection criteria and ranking the suppliers (Lam et al., 2010). Integrated TOPSIS and AHP have been used for supplier selection using price, time, and performance as selection criteria. AHP has been used to rank the hierarchy of supplier selection problems provided by the TOPSIS method (Tan et al., 2021). As highlighted by Ishizaka & Siraj (2018) and Noorzai (2023), AHP is the most relied upon MCDM method by experts and users due to its flexibility and consistency of results. In a similar study, Zhao et al., (2019) have integrated BIM and AHP for supplier selection. The authors highlighted that through a structured and systematic framework for decision-making, biases could be mitigated and consistency ensured in the evaluation process. Accordingly, AHP is used in the current study for a similar purpose.

2.4 BIM for supplier selection

BIM has emerged as a panacea to many construction problems. It enables precise decisions and ways to deal with the procurement cycle, cooperative plan, coordinated decisions, situation analysis, product correlation, documentation, automation, contract procedures, and execution (Aguiar Costa & Grilo, 2015). BIM-based solutions can reduce the adverse effects of the fragmentation of the construction project lifecycle by integrating information across the procurement processes (Grilo & Jardim-Goncalves, 2011). BIM, coupled with procurement management, can efficiently handle issues such as cost estimation (Abanda et al., 2015; Al-Mohammad et al., 2023). Moreover, BIM can effectively incorporate the MCDM methods for evaluating multi-criteria decision problems (Tan et al., 2021).

BIM has been integrated with Geographic Information System (GIS) to calculate material quantities from a construction project model and locate the material supplier (Yichuan et al., 2019). Figueiredo et al. (2021) integrated BIM and AHP to extract material specifications and quantities from a BIM design and rank the material suppliers. Zhao et al. (2019) demonstrated the effective use of BIM in dealing with the supplier procurement process in construction. Initially, a list of evaluation criteria was formulated to evaluate the suitability of material providers. Then, BIM was utilized to offer adequate data about the project requirements and providers' profiles. Finally, AHP was used to rank the material suppliers. The pertinent research, however, only demonstrates the selection of suppliers, while the search for suppliers has not been addressed. Also, the process is manual and non-interoperable, thus prone to errors and less practical to utilize in the field.

Considering the above studies, it is concluded that the issues in traditional supplier procurement management, such as ineffective communication, time-consuming manual processes, planning carelessness, legal and technical non-compliance, communication barriers, and corruption, can be minimized using digital technology like BIM. Similarly, issues such as complex selection processes, errors in calculations and estimation, and lack of competence among suppliers can be resolved by an MCDM-based ranking system. Further, issues like oversights, clashes, and errors in documentation, data gathering, and manual supplier searching can be addressed using automated information retrieval and web crawling techniques.

3 Research Methodology

The framework proposed by Ali et al. (2020) and Salman et al. (2010) for construction management research is adapted to suit the specific needs of this study. The methodology depicted in Fig. 1, begins with problem identification through a literature review and expert surveys. Subsequently, a supplier search and selection framework is proposed, leading to the development of a prototype. Finally, the prototype is tested on a case project and refined based on industry feedback, ensuring practical applicability and effectiveness.

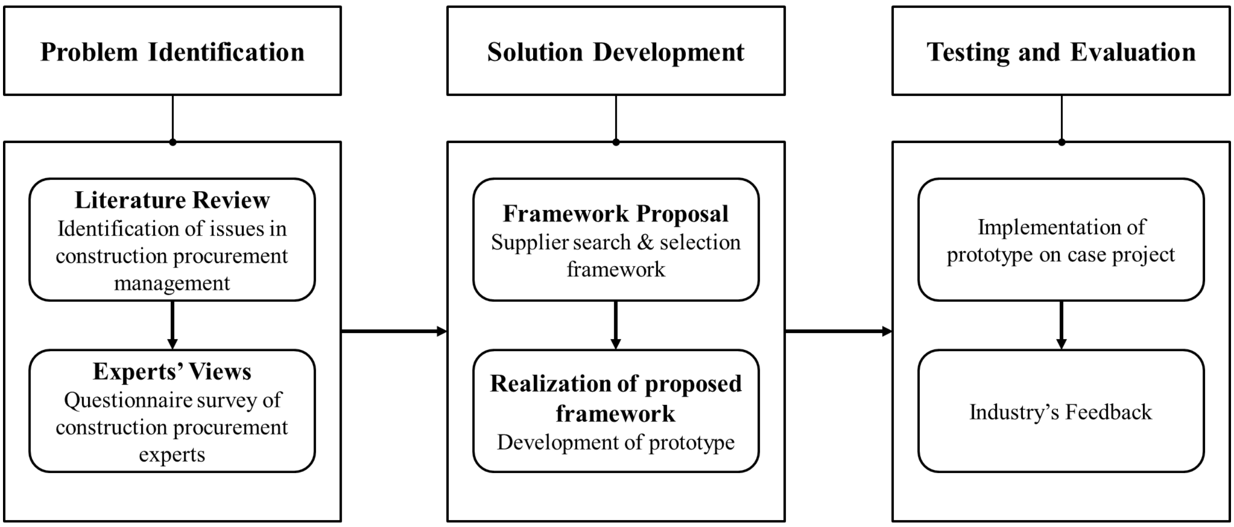


Fig. 1 Research Methodology Framework (Source: authors own work)

3.1 Identification of issues in construction procurement management

Firstly, the literature was reviewed in a semi-systematic way to identify issues and drawbacks in traditional procurement procedures. These issues were identified in overall procurement processes to encourage the BV procurement of material suppliers instead of traditional low-bid procurement, including procuring contractors, sub-contractors, and material suppliers. Literature was retrieved from scientific libraries such as Scopus, Web of Science, and Google Scholar. The search keywords used were: ("issues" OR "barriers" OR "drawbacks") AND ("procurement" OR "procurement management") AND ("construction industry" OR "construction sector" OR "construction"). The search explored the title, abstract, and keywords sufficient to identify and extract the relevant articles published in the last two decades. Three hundred forty articles were identified in the beginning, and then conference papers and book chapters were omitted to boost the quality of the review. Moreover, only peer-reviewed articles in English were selected, leading to 130 articles. Thirty-one issues in the traditional construction procurement processes were identified from these articles. It was followed by content analysis to combine overlapping problems, leading to the shortlisting of 23 relevant issues.

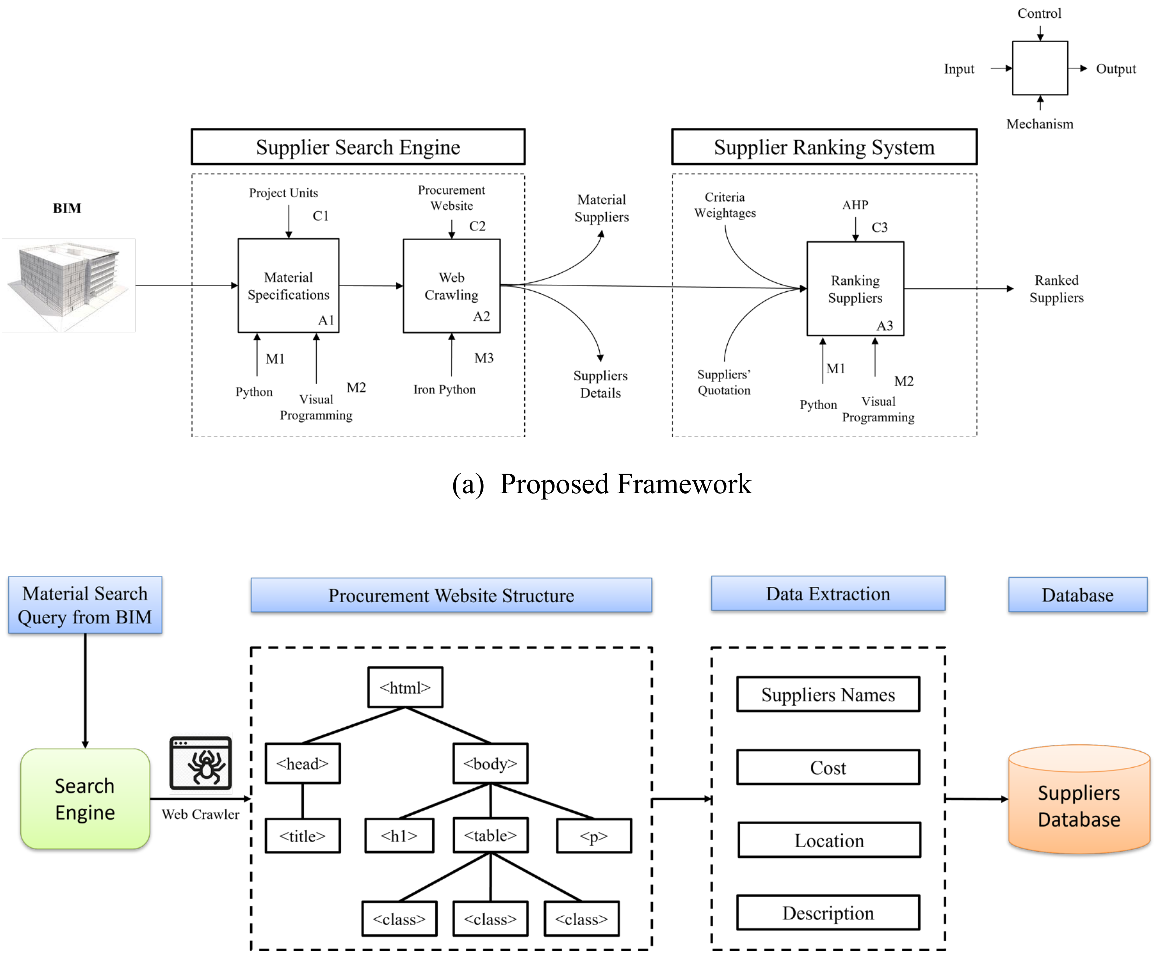
Next, the identified issues were processed through a pilot survey and presented to thirty-two procurement and supply chain experts in the construction industry (profiles shown in Table 1), following Naveed & Khan (2021). The respondents were asked to rate the occurrence and severity of each issue using a Likert scale of 1 to 5, 1 being the issue is not serious and 5 being very serious. The averages of all responses were used to calculate the normalized scores for each issue and subsequent ranking. Various weighting splits were utilized to find the cumulative scores of each issue, such as 30/70, 40/60, 50/50, 60/40, and 70/30 (literature/industry). The statistical variation between the ranks of issues in the various weighted splits was checked using the One-Way ANOVA test. The p-value of 0.998 indicated no variation in the ranking. Giving due importance to the views of field experts, a 30/70 weightage split was used. Thirteen significantly severe issues in traditional procurement methods were selected above a sixty percent cumulative score to comprehend the maximum impact following Ahmad et al. (2018).

Table 1 Respondents' profiles of the pilot survey and interviewed construction professionals. (Source: authors own work)

Group	**Count and Designation**	**Experience in years**
	Pilot Survey Respondents	
Contractor	11 x Procurement Manager	8 – 16
	7 x Supply Chain Manager	6 – 21
Consultant	3 x Procurement Manager	3 – 15
	5 x Supply Chain Manager	5-11
Client	2 x Procurement Manager	3 – 12
	4 x Supply Chain Manager	6-18
	Interviewed Construction Professionals	
Contractor	1 x Construction Manager	24
	1 x Construction Manager	10
	1 x Supply Chain Manager	17
	1 x Inventory Manager	11
	1 x Inventory Manager	12
Consultant	1 x Procurement Manager	21
	1 x Procurement Manager	24
Client	1 x Project Manager	12

3.2 Framework Development

A multi-stage framework has been developed in the current study for an automated construction material supplier search and selection. Three automated stages were involved in the process, as shown in Fig.2 a. These include (1) extraction of material information from BIM, (2) development of a construction material supplier search engine, and (3) deployment of a supplier evaluation and ranking system.



(b) Framework for web crawling

Fig. 2. (a) Proposed framework for supplier selection and (b) web crawling

(Source: authors own work)

In stage 1, an algorithm is devised to extract material specifications and quantities from a BIM model of a construction project based on predefined parameters. This information provides a search query for the online websites to procure the required materials. In stage 2, a web crawler is developed and deployed to get the available material suppliers (Fig. 2b). The crawler was specified with the location of each piece of information embedded in the website structure, giving it the capability of web scraping.

Stage 3 included a framework for ranking the searched supplier based on predefined selection criteria. As discussed in the previous section, AHP is used to evaluate and rank suppliers. Following the steps of AHP, presented by Saaty (2002), the listed steps were followed :

1. Defining the goal of the problem in question clearly, i.e., supplier selection in this study.
2. The issue is disintegrated into a hierarchy constructed on different levels. The highest level addresses the issue's objective, which is supplier selection. The criteria for supplier selection are listed in the middle. The last level shows the alternatives that are being judged according to the selected criteria.
3. To show the significance of one criterion over the other, a pairwise comparison can be settled on through a decision framework. With the assistance of decision-makers and field specialists, the dynamic framework is developed based on a nine-point scale, displayed in Table 2.
4. In the hierarchal construction, the components that underlie the normal node are compared with the other components of a similar node.

Table 1 Nine-Point Scale for Pairwise Comparison (Source: Saaty (2002))

Intensity of Importance	Definition
1	Equal Importance
3	Moderate Importance
5	Essential Importance
7	Very Strong Importance
9	Extreme Importance
2,4,6,8	Intermediate Values

Suppose there are $X_1, X_2, X_3, \ldots Xn$ factors within the node "N" and their statistical weights are $w_1, w_2, w_3, \ldots w_n$. The pairwise comparison of these factors according to their relevant weights is illustrated in the form of a matrix in eq.1 and eq.2, where Z is the comparison matrix (n x n) that symbolizes pairwise comparisons between the elements $X_1, X_2, X_3, \ldots X_n$:

X1 X2 Xn

$$Z = \begin{bmatrix} w1/w1 & W1/W2 & W1/Wn \\ W2/W1 & W2/W2 & W2/Wn \\ W3/W1 & W3/W2 & W3/Wn \end{bmatrix} \quad \text{----- eq. 1}$$

X1 X2 Xn

$$Z = \begin{bmatrix} a11 & a12 & a1n \\ a21 & a22 & a2n \\ a31 & a32 & a3n \end{bmatrix} \quad \text{----- eq.2}$$

Where $a_{ij} = w_i/w_j$ (i, j = 1, 2 … n) denotes the measured comparative importance between the pair of elements X_i and X_j. If i = j, then $a_{ij} = 1$ and $a_{ij} = 1/a_{ji}$ for $a_{ij} > 0$.

5. After developing the decision-making matrix, the next stage is to recognize the factors' priority weights using the maximum eigenvectors and eigenvalues, using eq.3.

According to Thomas L Saaty (1993):

$$\lambda = \sum_{j=1}^{i} aij \frac{Wj}{Wi} \quad \text{------ eq.3}$$

6. The consistency of the pairwise comparisons is confirmed in this step. In the pairwise comparison, the inconsistency is measured by the consistency index (CI), and the soundness is measured by the consistency ratio (CR). These are calculated with the assistance of formulas in eq. 4 and eq. 5:

$$CI = \frac{\lambda \max - n}{n-1} \quad \text{----- eq.4}$$

$$CR = \frac{CI}{RI} \quad \text{----- eq.5}$$

Where n is the rank of the matrix.

The maximum tolerance limit of CI and RI is 0.1 (Saaty, 1993). If the value is more than 0.10, it will show that the pairwise comparison is inconsistent and hence abandoned. For different values of 'n', the respective values of RI are described in Table 3 (Saaty, 1993):

Table 2 RI values for respective 'n' values used in AHP (Source: Saaty (2002))

N	2	3	4	5	6	7	8	9
RI	.00	.58	.90	1.12	1.24	1.32	1.41	1.45

7. After identifying the priority weights of each factor, which are the local weights of factors, the next step is to identify the global weights of all elements in accordance with the goal specified in the AHP model.
8. Finally, all the factors are reorganized in descending order according to global prioritization.

Since the industry lacks consensus on the criteria for construction supplier evaluation and selection (Polat et al., 2017), past studies were explored to determine the most cited supplier selection criteria. The previously mentioned literature platforms were used with conditional search query "Construction" AND "Supplier" OR "Vendors" AND "Selection Criteria" OR "Evaluation Criteria" OR "Selection" OR "Evaluation" between the years of 2000 and 2022. After carefully reading twenty-seven research articles, twenty supplier selection criteria were shortlisted based on mentioning in at least five studied articles. Multiple interlinked criteria were grouped under five major supplier selection criteria that were dominant in the construction industry in judging a supplier's capability following the procedure of Nursal et al. (2016). These include *cost*, *delivery time*, *experience*, *compliance with quality management standards, and warranties and claim period*.

Cost refers to the expense of the material quoted for procurement. *Delivery time* refers to the total time required to serve the material to the site. *Experience* refers to the tenure of the material supplier in the industry. *Compliance with quality management standards* refers to material compliance validation with the mentioned standards in the request for quotation form. Finally, *Warranties and claim period* refers to the period in which the warranty of the material can be claimed.

Eight local construction professionals (see Table 1) were interviewed to assess the significance of each criterion compared to the others for ranking the suppliers using the AHP method following Zhao et al. (2019). These professionals were carefully selected with more than ten years of experience in construction and/or procurement management. They were presented with the research objectives and asked to validate the present supplier selection criteria and assign weights to each criterion to develop a pairwise comparison matrix.

As a result, the AHP hierarchy was developed to rank and select suppliers based on the predefined criteria and their respective weights. These weights and suppliers' quotations are further normalized and checked for consistency to get the final ranks of the suppliers. The framework proposed in this study, as shown in Figure 3, is inspired by the works of Elshafei et al. (2022) and Ho et al. (2006).

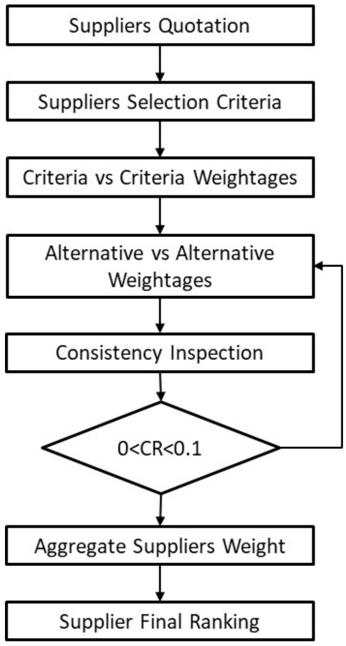


Fig. 3 Framework for AHP ranking system (Source: authors own work)

3.3 Framework deployment and proof of concept

Search and ranking algorithms were developed using Python programming language to automate the supplier selection process as part of the proposed framework. These were integrated within the BIM User Interface (UI) to apply the proposed framework. This resulted in the development of a prototype plugin, BIM-SSR, that was validated using a real-life case study to assess the extent of minimization of the targeted procurement issues. To further strengthen the validation process, the working of the developed prototype was demonstrated to the key stakeholders of the case study project. The capability of this prototype is to address the identified issues of the case study project, provide a proof-of-concept, and validate the proposed research framework.

A residential project for student hostels in a commercial area of Islamabad, Pakistan, was selected to demonstrate and prove the concept of BIM-SSR. It was a four-story building with a reinforced concrete floor slab, columns, and beams. Brick masonry separation walls and wooden doors and windows were used. The structure was in the conceptual design phase. It was a suitable candidate for planning the material procurement process.

First, a BIM model was designed for this construction project, and the working of BIM-SSR was demonstrated to key project stakeholders. Then, material suppliers were searched and ranked using the plugin, and working was demonstrated to the on-site professionals to discuss the various possibilities of suppliers' selection for a BV procurement. Eight on-site professionals were cautiously chosen for interview: five experienced construction experts, including three engineers and two managers with a minimum of fifteen years of experience in construction management, and three experts with knowledge and experience of at least five years in BIM. Face-to-face and online meetings were arranged with the on-site professionals to demonstrate the working and functions of BIM-SSR with the help of instructions, presentations, and videos. This subjective approach, as adopted by Ali et al. (2020), was selected to capture experts' opinions and perceptions. The minimization efficiency of traditional procurement issues through BIM-SSR was also discussed with the experts. The experts responded on a five-point Likert scale, giving an opinion on the issue resolution capability of developed BIM-SSR in the procurement management process. The results were converted into average scores and percentages for a better understanding. The success of the research framework was evaluated based on these average scores and percentages.

4 Results and Analysis

4.1 Issues in traditional construction procurement management

The issues in current construction procurement management were comprehensively explored in proposing the robust framework. A semi-systematic literature review, discussed in the methodology section, was applied along with validation from industry experts. The novelty of these results lies in the determination of the problems and issues in the current construction procurement management since no dedicated study was found on the matter. After assessing identified issues in procurement management, the 13 most significant issues were deduced based on sixty percent cumulative literature and expert scores as explained in the method section (See Table 4). The issues were selected with a focus on value-based procurement criteria, targeting supplier selection factors such as quality, compliance, reliability, and value (Madushika et al., 2020; Malacina et al., 2022).

Table 4 Issues in Traditional Procurement Management (Source: authors own work)

No.	Issues	Potential Reasons/Triggers	Selected Refs
1	Poor collaboration among stakeholders	The procurement methods are less collaborative due to distant offices, offline works, manual prints, approvals, and evaluations.	(Akenroye et al., 2019; Chan et al., 2019)
2	Ineffective data communication	Construction data is not communicated precisely and efficiently, which affects procurement cycles, code compliance, product evaluation, etc.	(Bao et al., 2019; Chan et al., 2019)
3	Time wastage and Delays	The procurement, search, or selection methods take more time than planned, delay supplies and execution due to slow and tedious work, and sometimes lead to a temporary project halt.	(Akenroye et al., 2019; Sayed et al., 2019)
4	Errors and mistakes in “Manual” Calculations and Estimation	The manual methods of quotations, requests, and calculations contain chances of human errors, leading to incorrect estimates and mathematical calculations.	(Aguiar Costa & Grilo, 2015; Sayed et al., 2019)
5	Inefficient traditional methods of procurement	The traditional procurement methods do not meet expectations and do not produce the desired results within the targeted time and budget.	(Afolabi et al., 2019; Sayed et al., 2019)
6	Corruption and non-transparent processes	The subjective selection of contractors, sub-contractors, and suppliers is open to abuse and corruption.	(Afolabi et al., 2019; Bao et al., 2019)
7	Expensive and costly	The manual, laborious, time-consuming, repetitive, and error-full procurement processes incur more costs.	(Aguiar Costa & Grilo, 2015; Bao et al., 2019)
8	Poor efficiency of construction works	The existing methods are ineffective in getting the expected results, competent suppliers, and on-time deliveries. This leads to poor quality products, non-compliance to standards, delays in replacements and claims, and low efficiency in construction works.	(Adedeji Afolabi et al., 2019; Sayed et al., 2019)
9	Procuring non-complaint services and material	Leniency in legal and technical construction, safety, or sustainability standards while evaluating the contractors, subcontractors, and suppliers can lead to procuring non-complaint services and materials.	(Afolabi et al., 2019; Suresh Tiwari et al., 2018)
10	Selecting the right person for the job	Incompetent contractors, sub-contractors, or material suppliers can be hired due to mistakes in evaluation, leniency in standard compliance, manual, and corruption.	(Bao et al., 2019; Suresh Tiwari et al., 2018)
11	Low-profit margins for project stakeholders	Loss of profits due to manual and resource-consuming procurement processes, delay claims, project halts, paper-based work, and corrupt practices can dent stakeholders’ profit margins.	(Akenroye et al., 2019; Sayed et al., 2019)
12	Complicated procurement processes	The processes leading to procurement are complicated, not easily understandable, laborious, and confusing, hence prone to errors.	(Aguiar Costa & Grilo, 2015; Sayed et al., 2019)
13	Improper “Change management” systems	Improper management systems for changes and variations in project design or construction specifications lead to inadequate management and proper communication of changes to the contractors and sub-contractors.	(Aguiar Costa & Grilo, 2015; Suresh Tiwari et al., 2018)

4.2 BIM-SSR Prototype Architecture

For the proof-of-concept and validation of the proposed BIM-based search and selection framework, an innovative prototype, BIM-SSR, was created in Autodesk Revit (see Fig. 4). The BIM-SSR has two components: The Search Engine and Rank component which are subsequently explained. It integrated the proposed framework for automated procurement of construction material suppliers and vendors from the World Wide Web (WWW) into Revit to minimize the identified issues in traditional procurement methods. Previously, no such automated framework has been proposed that aims to resolve the issues in the current supplier procurement processes using digital and innovative tools like web crawling and BIM.

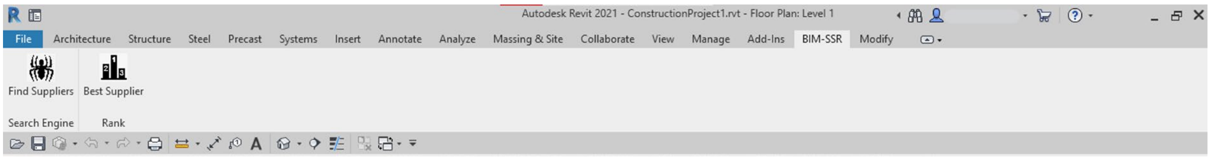


Fig. 4 BIM-SSR User Interface (Source: authors own work)

4.2.1 Search Engine Component

The BIM-SSR's search engine includes a "Find Suppliers" tab that operates in two phases. In the first phase, all the BIM model elements are listed in the repository after categorization using the parameter function, such as description, volume, area, count, etc. This generates the final list of all the elements, materials, specifications, quantities, and units. The construction material data extracted from the BIM model is represented as a pop-up window within the BIM platform and exported in a. CSV file.

In the second phase, there is an option to choose the material needed to be procured. This selection generates an automated search query to crawl the online suppliers, including the material's name and the technical specifications defined in the model. Then, a web crawler is utilized to search for material suppliers on the WWW, which looks into the selected procurement websites and searches for profiles based on the search query. Finally, the website's structure is distributed into its HyperText Markup Language (HTML) body, containing headers, titles, paragraphs, and various classes with information embedded within the structure. The crawler identifies the path of required information in each advertisement or listing and indexes the information in the following format:

- Suppliers' name
- Suppliers' address
- Material price as shown in the advertisement
- Material advertisement description for *experience* and *compliance with quality management standards.*

- Web link to the profile for contacting the supplier, for delivery time, warranties, *and claim period.*

4.2.2 Rank component

The rank component in this study consists of a "Best Supplier" tab added to the BIM-SSR interface with Revit. It is programmed with AHP calculations following the process explained by Saaty & Hu (1998), with suppliers' quotations and criteria weights in a pairwise comparison matrix as inputs. First, the value for each criterion weight is normalized and checked for consistency, giving its total weight. Then, quotations from the suppliers are compared and normalized to determine their local weights. The aggregate of both these weights is utilized to define the final ranks of respective suppliers as the final output of the component. These calculations are linked with the criterion vs. criterion weights specified by the experts and the quotations of material suppliers that help rank these suppliers following the standard AHP procedure. Finally, the results are displayed within the BIM platform, including the project material list, searched material suppliers, and final ranks of these suppliers, thus aiding the selection of the best supplier.

4.3 Prototype Evaluation and Proof of Concept

The application of BIM-SSR on a BIM model was demonstrated to the on-site professionals of the case study facility. Firstly, using the architectural plan of the building, including material specification as per the contract, a list of 774 building elements and the quantities of their respective materials were extracted. Common Brick TMS 602 was selected to demonstrate online procurement through the BIM-SSR material selection UI. A commercial website operating in 45 nations called "OnLine eXchange" was selected to procure construction materials for demonstration purposes. The website's structure contained various attributes specifying the information embedded within it. The HTML body was queried using division and header tags containing various sections and subsections to extract the suppliers' information under these tags. The developed web crawler was coded to identify the paths of the required information within the HTML body and enlist them in the specified format discussed previously. The web search resulted in extracting details of four online material suppliers.

Then, the suppliers' respective names, locations, prices, and descriptions were listed in the BIM-SSR through Revit. The *cost* of the required quantity of bricks ranged between Rupees

22,544,000 to 34,347,500. In addition, the suppliers' *experience* and *compliance with quality management standards* were extracted from suppliers' profiles from the selected pre-approved webpage. These were all government-approved suppliers who met all quality standards, thus eliminating the risk of selecting any unqualified or non-compliant supplier. Further, the suppliers' *delivery time*, *warranties, and claim period* were requested using a website link extracted through web crawling, as shown in Table 5.

Table 5 Suppliers' quotations on required material and pairwise comparison of criteria

(Source: authors own work)

	Cost	**Delivery Time**	**Compliance with Quality Management Standards**	**Warranties and claim period**	**Experience**
	Rupees	Days	Quantity	Years	Years
Suppliers' quotations on required material					
Supplier 1	34,347,500	5	2	8	5
Supplier 2	23,445,700	10	1	5	8
Supplier 3	23,085,000	12	2	6	20
Supplier 4	22,544,000	4	2	3	14
Pairwise comparison matrix of criteria					
	Cost	**Delivery Time**	**Compliance with Quality Management Standards**	**Warranties and claim period**	**Experience**
Cost	1	2.25	3.75	4.87	7.25
Delivery Time	0.45	1	2.75	4.50	7.625
Compliance with Quality Management Standards	0.27	0.36	1	2.13	4.75
Warranties and claim period	0.21	0.22	0.47	1	4.88
Experience	0.14	0.13	0.21	0.21	1

As mentioned in the methodology section, the criteria were compared using values obtained through interviews of eight on-site professionals. The assigned values for each criterion are averaged, giving their final importance. For instance, the *cost* compared to *delivery time* is 2.25, illustrating that cost is 2.25 times more important than the *delivery time of the material*. All criteria assessed against themselves were given a value of 1 following the standard AHP process. Finally, a pairwise comparison matrix was produced using these results, shown in Table 3.

Using BIM-SSR, the eigenvector was calculated automatically to get the criteria's weights using normalization and check the consistency of the results. The consistency ratio value of 0.0937 (CI=0.105; RI=1.12) indicated that the construction professionals' judgment was consistent, and the criteria weights were reliable. Following the above, the suppliers' final aggregate weights and ranks were indicated using automated calculation of local weights for each supplier. The results of material extraction, search engine, and mathematical calculations of AHP are illustrated in a user-friendly window within the BIM platform. The aggregate weights of suppliers in the current case were 0.269, 0.285, 0.244, & 0.201, respectively. Accordingly, Supplier 2 was ranked as the best option and recommended for supplying the material for the project.

The first novelty of these results lies in the exploration of issues in the current supplier search and selection practices through a semi-systematic literature review. It was further strengthened by validating the intensity of the issues from the construction industry experts. Another novelty of the result can be deduced from the novel integration of web services with the construction management process using innovative digital technologies like web crawling and BIM. Also, research methods like AHP were automated and integrated within the BIM platform to rank the web-based suppliers. These multi-fold novelties provide innovation in supplier search and selection procedures and help automate construction procurement management.

5 Discussion

After demonstrating how BIM-SSR works, the on-site professionals were asked to present their opinions on the developed BIM-SSR efficiency to tackle the procurement issues identified in this study. Key comments are presented and discussed below.

- Most of the professionals assigned a value of 95% to BIM-SSR efficiency in resolving "*Time wastage and delays*" and "*Errors and mistakes in manual calculations and estimation*." Hence, BIM-SSR can efficiently tackle the issues identified in construction procurement.
- Issues such as "*Ineffective data communication*," "*Corruption and non-transparent processes*," and "*Improper change management systems*" in construction procurement are ranked second to be efficiently solved using BIM-SSR, with a percentage efficiency

of 92.5%. This shows that the communication barrier is reduced to a considerable extent by using BIM-SSR. Moreover, change in design is effectively managed through BIM-SSR at any stage of the construction since it will always extract the exact specifications and quantities of the project. This can help assess any variations in the design.

- The third-ranked issues being resolved with an efficiency of 90% through BIM-SSR are "*Inefficient, traditional methods of procurement*," "*Poor efficiency of construction works*," and "*Complicated procurement processes*." These are all related to the innovative approach of the proposed procurement process, showing that procurement through BIM-SSR is considerably efficient compared to traditional methods.
- The conformity of material specifications and certification of suppliers leads to the resolution of the "*Procuring non-complaint services and material*" issue. It is ranked fourth by experts and can be solved by the BIM-SSR prototype, with an efficiency of 87.5%.
- The issue of "*Selecting the right person for the job*" is ranked second last because the experts are reluctant to purchase material using online services from the selected website, as indicated by the interviewees. However, this could easily be addressed when this research is implemented on a worldwide construction website or in a country where the material suppliers are already procured using online services.
- The capability of solving the "*Low-profit margins for project stakeholders*" issue was the lowest ranked; however, the efficiency of 80% assigned to BIM-SSR for tackling it is still high. The reason was the apparent competitive environment of BIM-SSR, leading to lower profit margins. Nevertheless, BIM-SSR is a low- or no-cost investment and includes a cost-saving process that can be included in profit margins for stakeholders.

The mean scores for BIM-SSR assigned by the professionals are all positive (within the range of agreed or strongly agreed), showing that BIM-SSR is a highly efficient tool for resolving the issues in traditional procurement of construction material suppliers. Conventional issues like *time wastages*, *errors due to manual calculations*, and *ineffective data communication* can be resolved using the BIM-SSR due to its automated, precise, and quick processing. Further, while targeting such issues, the BIM-SSR enhances the whole supplier search and selection process by making the system transparent, detecting changes, and improving the supply chain management process. This was confirmed by the interviewees when they were asked to quantify the effectiveness of BIM-SSR in enhancing the procurement management procedure in the construction industry. Accordingly, they believe BIM-SSR is 97.5% effective in improving the procurement management process. They concurred that the proposed framework and the prototype stand out in terms of novelty and practicality by specifically targeting problems in the industry and efficiently resolving them using innovative digital technologies and automated methods. Both supplier search and selection frameworks align with the current procurement practices, providing ease of communication and helping the industry to move towards data scientific and digital advancements.

Compared to extant literature, the current study adds to previous research, such as Zhao et al. (2019), who developed a similar methodology to optimize the supplier selection process. Specifically, in the published study, the list of supplier selection criteria was not validated, and BIM was utilized to access only the data of a construction facility. Moreover, AHP was not programmed using Python to assess the suppliers automatically. In comparison, the current article has utilized BIM to automate the end-to-end procurement process using industry-validated BV supplier selection criteria for AHP. Moreover, the introduction of a web crawler for supplier search is a novelty that has not been reported so far by others. Previously the authors have used web crawlers for the collection of images (Hwang et al., 2023; Park et al., 2023), transportation network data (H. Wang et al., 2022), media scraping (Dou et al., 2019) etc but never for soliciting BV suppliers which is an innovation exclusive to the current study.

This study pursued three key objectives aimed at advancing the digitization of construction procurement management. The primary objective was to develop a dedicated framework and prototype that would facilitate the search and selection process of construction material suppliers by leveraging the rich data and visualization capabilities offered by BIM systems. To achieve this, the research identified and investigated the current issues in traditional supplier selection as objective one of the studies. Industry experts were engaged to ensure that the identified issues are applicable to the industry and validate them for further research. Afterward, as objective two, a BIM-based end-to-end supplier selection framework (BIM-SSR) was developed to address the identified issues. This system was strategically developed to enhance digitization in the industry, integrating BIM technology, supplier search methods, and MCDM-based evaluation of the suppliers.

With a focus on value-based procurement, the supplier selection criteria prioritized factors such as quality, cost-effectiveness, sustainability, and reliability. Through rigorous experimentation and validation from industry experts, the automated system was improved to address the concerns associated with manual, time-consuming, and error-prone methods of supplier selection. By leveraging advanced computational tools and a real-world case study, the study elucidated the transformative potential of BIM in optimizing construction procurement management, improving coordination among stakeholders, and minimizing errors during procurement phases. Finally, the framework was reviewed by industry experts to identify its capability to resolve the targeted issues and close the loop. By achieving these objectives, the research contributes valuable insights to the fields of construction procurement and supplier selection and brings in much-needed innovation in the otherwise tech-averse industry. It also offers actionable recommendations for industry practitioners and policymakers striving to foster sustainable, efficient, and digital construction practices.

6 Conclusion

Construction procurement processes are critical to the project's success. The conditions of each construction project demand technical and specialized evaluation of material suppliers, including thorough estimation of material supply, supplier search, different technical specifications for each project, time management of procurement process, and evaluation of material suppliers based on varying importance factors impacting project completion. If not dealt with precision, integrating such complex and error-prone processes results in the selection of unqualified suppliers, resulting in poor quality and inefficiency of construction works, lower profit margins for project stakeholders, and a corrupt business environment.

The study achieved the research objectives by addressing the challenges, which presented clear answers to the research questions. Firstly, the identification of key issues in the construction material supplier selection identified the critical challenges that needed to be addressed, thereby answering the first research question. This added scientific value to the field of research, since none of the previous studies provided answers to this critical question. Finding the issues in the current supplier procurement practices provides further research gaps for future studies. By offering a solution to the identified issues, the development of the BIM-based framework (BIM-SSR) directly responded to the second research question. In terms of research value, the framework demonstrated the capability of BIM to integrate web technology with supplier search and MCDM methods. Due to the introduction of these nascent capabilities, further integration of BIM, web, and MCDM through other disruptive digital technologies can be explored. The answers to the research questions were further validated by the experts using questionnaire survey and interviews, demonstrating the applicability and effectiveness of the proposed solution in a real-world scenario.

An automated BIM-SSR framework based on web crawling is devised to minimize the issues in construction procurement practices through a collaborative, centralized, and digital data management prototype named BIM-SSR in this study. The prototype is validated using a case study of a construction project and opinions from pertinent industry professionals. The BIM-SSR prototype developed using programming API is plugged into Autodesk Revit. Revit was used to extract material estimates and specifications from an architectural design of the case study construction project. Then, web services were used to search for suppliers for the required materials. Further, these suppliers were ranked using AHP based on five value-based criteria shortlisted through an extensive literature review and weighed by pertinent industry experts. These include *cost, delivery time, experience, compliance with quality management standards,* and *warranties and claim period*.

The proposed BIM-SSR facilitates seamless supplier search and evaluation of material suppliers and provides accurate information regarding material specification, quantity, dimensions, orientation, and placement with bounding materials and elements. This ensures 100% accurate data provision to the project managers and stakeholders to help them make informed decisions. The suppliers selected based on such accurate information can be highly reliable and responsible, allowing competitiveness among suppliers, transparency in business, compliance with technical standards, highly managed supply chain and change management systems, and eventually, a better quality of work. Moreover, the automated criteria-based evaluation of suppliers strengthens the decision-making process with error-free calculations and reduces supplier selection time.

7 Implications

7.1 Practical Implications

The developed BIM-SSR offers several practical implications. It offers an advanced construction suppliers' search engine where the Internet can be utilized to procure the required construction material worldwide. The web crawler adopted in this study is a practical tool for automating the search process by using accurate estimates and specifications of materials extracted from a BIM model. The list of facility materials is tabularized for the procurement manager, including material quantities and specifications that reduce the search time, cutting the cost of the process, omitting any chances of errors or mistakes in data gathering and transferring, providing accurate material information, and gathering suppliers' information for the evaluation and selection process. The construction material supplier evaluation feature of the BIM-SSR prototype is another practical advantage. The selection of a responsible and competent supplier for the required material is essential for the success of a construction project in terms of cost, quality, and time. These value-based procurement criteria, which look beyond cost for the selection of construction material suppliers, provide a supplier prequalification strategy enhanced by automated calculations for error-free and timely calculations within a collaborative BIM environment. This helps in a cost-effective, less complicated, and transparent selection of the most suitable construction material suppliers, resulting in increased quality of work within budgeted cost and time.

7.2 Research Implications

In terms of research implications, the article provides a list of issues apparent in traditional construction procurement practices that future researchers can further investigate as stand-alone topics. Further, the current study merges traditional construction procurement practices with digital technologies through a framework that can be further broken down into researchable components such as web crawlers used in the construction process, BIM-supplier linkage, and automation of value-based procurement. Future studies can build on this to move towards the much-needed construction innovation in line with Industry 4.0 and 5.0 goals. This research also opens doors for further research on enhancing the search engine capabilities of BIM.

8 Limitations

The study explores the issues in current construction material supplier procurement practices using a systematic literature review, content analysis, and questionnaire survey. However, a dedicated study on the current problems in construction procurement is needed using a detailed systematic literature review. The BIM-SSR prototype is limited to data acquisition from a specific website. Further, the case study is limited to a specific location. The web crawler is programmed according to the considered website structure and locality and will require changes in its algorithm for other supplier procurement websites. Moreover, the literature lacks universally accepted supplier selection criteria. Therefore, the varying supplier selection requirements in each construction project might need modification of project-specific criteria in the proposed prototype.

9 Future Directions

The research is a steppingstone for enhancing conventional supplier search and selection processes using modern digital technologies. It opens research domains of BIM-enabled search engines and automated supplier selection methods. In the future, open web data can be integrated with BIM to enhance information management in various construction management processes. Moreover, contractor selection can also be researched using the same framework.

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