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Promoting the Application of Big Data in Construction through Stakeholder Collaboration Based on a Two-Mode Network

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Abstract: Presently, the application of big data in the construction industry encounters numerous obstacles and involves diverse stakeholders, with the intricate network of relationships between these factors and stakeholders remaining unclear. Investigating stakeholders' management priorities and collaborative patterns can facilitate the development of BDAC. Therefore, this study employs a two-mode social network analysis to explore stakeholders' power and attitudes toward the factors of BDAC. Firstly, the initial list of stakeholders and factors is identified based on the literature and expert interviews, followed by a questionnaire to establish stakeholder–factor relationships and construct the network. Subsequently, the adjacency matrix, centrality, core–periphery structure, and hierarchical cluster are adopted to analyze the network. The results found that (1) technical factors need to be addressed by all stakeholders due to complexity; (2) due to the low resource similarity of factors and low power similarity of stakeholders, all stakeholders should be involved in the collaboration; and (3) government, developers, and consultants, as core stakeholders, exhibit a proactive inclination towards collaborative efforts in addressing central factors, and can coordinate with peripheral stakeholders. Consequently, this study establishes a stakeholder collaboration model centered on the government–developer–consultant trio, which provides clear responsibility allocation and strategic guidance for fostering long-term, effective collaboration in BDAC.

Keywords: construction; big data; stakeholders; factors; cooperation

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1. Introduction

In recent years, big data application (BDA) has widely attracted the attention of various fields [1]. In the age of digital technology, a great deal of data are generated and accumulated [2]. These data enable researchers and practitioners to make informed decisions and conduct relevant analyses for their field [3], which is no exception for the construction industry. Big data in construction (BDC) refers to the vast amount of intricate, specific, and professional data generated throughout a building project's entire life cycle [4], encompassing design information, schedules, Enterprise Resource Planning (ERP) system data, financial records, and construction data [5]. BDC has six defining attributes (also known as the 6Vs): volume, variety, velocity, variability, validity, and value [6]. These data contain heterogeneous formats such as such as DWG (drawing), RM/MPG (video format), RVT (Revit), and DGN (design), among others [5]. With the adoption of technologies like building information modeling (BIM), radio frequency identification, cloud computing, sensor networks, etc. [7,8], the construction industry is entering the big data (BD) era [5,9]. The construction industry is currently suffering from inefficiencies, which leads to an annual global economic loss of $1.6 trillion [10]. The introduction of BDA can solve the extant problem [4]. BDA can also benefit the construction industry by improving decision making and optimizing management [6]. For example, some studies have used historical project data to develop strategies for controlling future project costs; BD can transform conventional construction operations into a more automated process [3]. Overall, BD have the potential to improve the construction sector in various ways, including construction safety, efficiency, productivity, competitive advantage, and more [11]. A survey indicated that approximately 75% of construction domain professionals regard the use of BDA as one of the most critical tasks in the future [7].

The application of big data in the construction industry (BDAC) seems to be unavoidable, but it is still in its infancy and has a long way to go before reaching maturity [3]. The construction industry is data-intensive and generates a lot of data [12]. However, these data are far from being fully utilized [8], since there are many obstacles to BDAC [13]. Through the literature review, obstacles such as the availability of BD technologies and facilities, government policies, data sharing, cooperation mechanisms among various stakeholders, etc., were found to have a significant impact on BDA. Understanding the factors influencing BDAC can help practitioners develop reasonable strategies and promote the digitization of the industry [14].

Existing studies have summarized and analyzed the factors influencing BDAC through interpretative structural modeling (ISM) and expert interviews. Currently, stakeholders play an important role in BDA, and their attitudes and abilities can significantly affect BDA [15,16]. Janssen [17] points out that the ability to collaborate among stakeholders is critical to overcoming the fragmentation of construction data and the formation of data chains. Furthermore, the lack of standardization of data from different stakeholders was found through expert interviews to be one of the most significant barriers to BDAC. The information and knowledge gathered from various stakeholders is a valuable data source for BD analytics [17,18]. Stakeholders' refusal to cooperate often prevents the introduction of innovative technologies in construction [19,20]. Existing studies are limited to the exploration of factors and their internal relationships, ignoring the importance of stakeholders in BDA. Investigating the factors of BDAC from the perspective of stakeholders can help us analyze the relationships between factors and stakeholders, which can help define the responsibilities of all stakeholders and develop effective strategies to promote BDA [21].

Stakeholder collaboration refers to the process by which they take action or make decisions on issues relevant to the field [22]. However, conflicting interests and intricate relationships between stakeholders can hinder collaboration [23], especially in the construction industry where stakeholder management is particularly challenging [24]. Thus, the analysis of the interactions between stakeholders through a network is critical because it explores their collaboration and salience [23,25]. Social network analysis (SNA) investigates social structures based on graph, anthropological, and sociological theories [26]. It is divided into one- and two-mode networks according to the type of nodes [27]. One-mode network models can only explore the interrelationships between the same set of entities [28]. A two-mode network is made up of two sets of heterogeneous nodes (representing the collaborators and the aim of their cooperation), which is useful for modeling and analyzing the relationship between the two groups [26]. It is already used in several aspects of research in the construction industry, such as building energy performance, off-site construction, etc. [28]. In most studies, the two types of nodes are stakeholders and events (barriers or issues) [27].

Therefore, this paper aims to carry out a two-mode network to investigate in-depth the relationships between stakeholders and the BDAC factors to find the attitude and ability of stakeholders toward each influencing factor and find the optimal governance path. The following are the main research content of this paper:

1. Identifying a list of stakeholders and factors of BDAC based on the literature review and expert interviews.
2. Investigating the relationships between the stakeholders and factors influencing BDAC through questionnaires.
3. Constructing two-mode networks from the perspective of stakeholders and analyzing the network's structure and characteristics to elucidate the role of each stakeholder.
4. Discussing future recommendations and promotion strategies for BDAC based on the analysis results.

2. Literature Review

2.1. Factors Influencing BDAC

In recent years, many studies have been conducted on the factors that influence BDCA. The TOE (Technology–Organization–Environment) framework has been widely used in existing studies to systematically categorize influencing factors [4,28]. Yu, Liang and Wang [13] identified the factors and interrelationships that significantly influence the adoption of big data in construction through ISM and Matrix Influence Cross Multiplication. The results indicate that relevant technologies, incentive policies, management support, and organizational structure are the factors that need to be focused on. Ahmed et al. [29] explored the challenges and key drivers of big data adoption in the architecture, engineering, and construction (AEC) industry through a comprehensive literature review and an expert workshop, and the results revealed the criticality of factors such as organizational structure change and willingness to share data. Boyd and Crawford [30] argued that the utilization of BD is influenced by factors such as the availability of BD technologies, privacy policies, and the mechanisms for information sharing. Furthermore, data sources serve as the foundation for BDA [17,31]. Data quality issues such as errors and omissions have emerged as a critical barrier to the advancement of BDCA [32]. Skilled engineers and proficient workers are also recognized as a prominent factor in its adoption in projects [33]. A data-driven culture is a crucial intangible resource for BDA, fostering an understanding among organizational members of its potential value [4,34].

The literature review found that existing studies have established a relatively comprehensive initial list of factors through literature reviews and expert interviews, but fewer studies have considered the economic dimension of cost factors. More importantly, while factor analysis has been given enough attention, the current research on BDCA factors does not consider stakeholders who play an essential role in managing these factors. There is a lack of studies examining the relationship between influencing factors and stakeholders.

2.2. Stakeholders in Factor Analysis

There are stakeholders from different disciplines and professions involved within the construction industry who almost determine the success of a project [35]. Stakeholder theory holds the key to more effective management, and it includes theories of stakeholder identification and salience (e.g., power, urgency, legitimacy, attitude, etc.) [21,36]. In recent years, research on stakeholder management in construction has developed extensively. For instance, Gan, Chang and Wen [28] investigated stakeholders' influencing power over barriers to off-site construction using a two-mode social network analysis. Lin, et al. [37] conducted an empirical analysis on the impact of responsible leadership on stakeholder collective performance based on questionnaires, offering practical recommendations to enhance stakeholder management in construction projects. El-Gohary, et al. [38] analyzed the importance of stakeholder management for the success or failure of government–social capital partnership (PPP) projects, and showed that consultants are closely related to the decision of technology introduction. Galjanić, et al. [39] developed a measurement framework that demonstrates the significance of multiple stakeholders in performance measurement and management. By integrating network analysis and empirical studies, researchers have illuminated the importance of effectively managing these diverse stakeholders to ensure project and technology success.

Though stakeholders have been introduced to analyze the factors in many fields, their importance has been neglected in BDAC. Current research on the factors of BDAC does not comprehensively take the influence of stakeholders into account. However, the perception of construction project success and the introduction of new technology is currently based on the perspective of accommodating stakeholder issues and achieving stakeholder satisfaction [40]. For example, Mok et al. [41] used social network analysis and found that the government and the design and construction contractor were the most influential stakeholders who are closely linked to the application of new construction technologies. To address the ethical issues of big data analytics, Asadi Someh, et al. [42]

used stakeholder theory to analyze the interrelationships between various stakeholders. Therefore, it is essential to consider the role of stakeholders in the process of big data application. In social networks, power is a critical attribute of stakeholders, which reflects one's capacity to change another's behavior or situation [43]. Stakeholder attitudes are also a salience that has a critical impact on the objectives of the project [44]. Thus, social network analysis, as an effective tool to analyze the interrelationships between factors and stakeholders, fills this research gap.

Based on the above literature review, BDA is critical to the construction industry, but it is far from satisfactory. Though existing studies have investigated the factors influencing its adoption, few studies explore the relationship from the perspective of stakeholders. How to manage these factors through collaboration among the stakeholders still remains unclear.

3. Methods

In this study, the two-mode social network was established and further analyzed through a literature review, expert interviews, and questionnaires. The specific flow is shown in Figure 1.

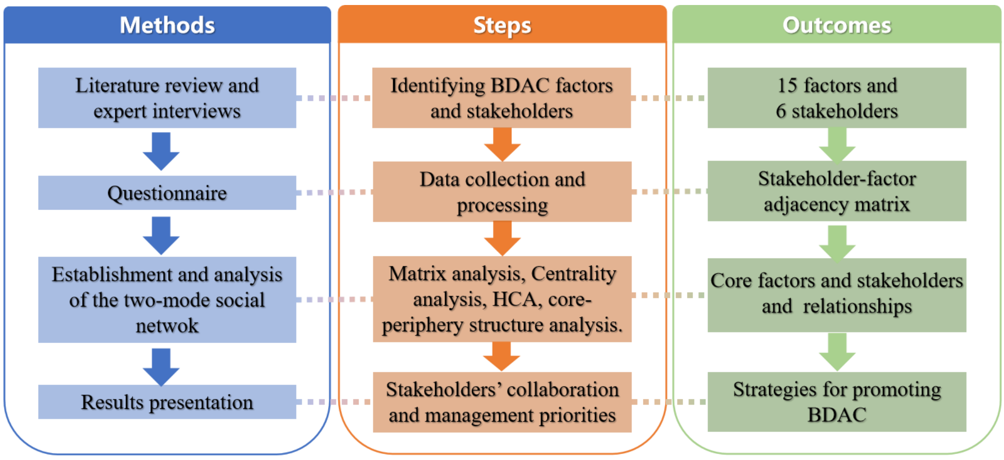


Figure 1. Research flow.

3.1. Identifying BDAC Factors and Stakeholders

A literature review and expert interviews were carried out to identify the influencing factors and stakeholders of BDAC. Firstly, a preliminary list of factors and stakeholders was obtained by collating the previous relevant literature. A systematic literature search was conducted in the Science Direct and Web of Science databases, combining keywords such as "factors", "barriers", "big data", and "construction". Subsequently, the retrieved articles were filtered based on relevance, and 27 of the most pertinent articles were finally selected.

Current research frequently employs the TOE (Technology–Organization–Environment) framework to systematically categorize influencing factors [28]. BDA in construction necessitates investments in infrastructure, technology, and human resources, which in turn incurs additional costs [45]. Therefore, this paper adds financial factors to the traditional TOE to construct a new TOEF (Technology–Organization–Environment–Financial) factors framework. As for the stakeholders, besides the government [29,40], developer [19], construction contractor [29], and design contractor [28], which have been often mentioned, El-Gohary et al. [38] found that the consultant is related to the technology introduction decision. Furthermore, considering BD technology as an emerging technology, cutting-edge scientific research results can provide suggestions and a basis for application. Ongoing technological innovation has the potential to significantly cut technical costs [46]. Researchers are crucial in converting a concept into an invention [27]. Considering that the construction industry is often accused of lacking innovation, this paper innovatively considers researchers as one of the stakeholders [46]. Finally, six stakeholders, including S1 (government), S2 (developers), S3 (construction contractors), S4 (designers), S5 (consultants), and S6 (researchers), were put forward.

Subsequently, the initial list was refined through semi-structured interviews with representatives from the previously identified diverse stakeholder groups. To ensure the representativeness and reliability of the collected data, each participant was expected to have sufficient knowledge regarding BD-related practices. The selected participants held positions at the middle management level or higher and had at least five years of professional experience. Ultimately, six experts were invited to participate in the interviews. Table 1 provides an overview of the six interviewees. The interviewees were invited to comment on the following topics: (1) whether there are ill-defined BDAC factors in the initial list; (2) whether there are any additional factors or stakeholders that could be added; and (3) whether any factors or stakeholders identified from the literature review are irrelevant to BDAC. The results of the interviews indicated that the opinions of experts and the literature are highly consistent. Meanwhile, some improvements have also been suggested. For example, data standardization and support from top management are key factors affecting BDAC, which should be supplemented. Finally, factors suggested by the experts include T5 (fragmented nature of construction data), E2 (standards and guidance), and O2 (support from top management). Based on these 27 articles, 15 factors under four dimensions were obtained after modifying the factors with inputs from the expert interviews, as shown in Table 2.

Table 1. Information of interviewed experts.

Expert	Stakeholders	Position	Years of Working
A	Government	Head of Intelligent Construction	15
B	Developer	Project Development Engineer	10
C	Contractor	Project Manager	12
D	Designer	Chief Engineer	14
E	Consultant	Vice President	19
F	Researcher	University Professor	20+

Table 2. Indicators of factors influencing the application of big data in construction.

Category	Factors	Description	Source
Technology (T)	T1 Availability of BD technologies	The technical tools and software support required for data collection, storage, processing, and analysis.	[5,17,47–49]
	T2 Availability of BD facilities	Effective IT infrastructure to support data collection, storage, processing, and analysis.	[13,17,32]
	T3 Data quality	Data reliability, timeliness, volume, etc.	[17,31–33,42,50]
	T4 Exemplary projects	Demonstrative projects with practical significance and valuable experience in applying big data in construction.	[13,50]
	T5 Fragmented nature of construction data	Data dispersion and diversity due to insufficient data sharing.	[13,51]
Organization (O)	O1 Organization structure	Relevant functional departments and roles aligned with BDA.	[4,32,34,47]
	O2 Support from top management	Approval and strategic support from senior leadership.	[32,52–54]
	O3 Human resources	Skilled staff and experts on big data.	[17,32,33,55,56]
	O4 Data-driven culture	A supportive organizational culture that fully appreciated the potential value of BDA.	[13,32,34,57]

Table 2. *Cont.*

Category	Factors	Description	Source
Environment (E)	E1 Willingness of stakeholders to collaborate	Stakeholders' willingness to actively cooperate and apply big data.	[13,17,45,50]
	E2 Standards and guidance	Relevant documents and specifications for standardized data analysis and application.	[13,17,33,58]
	E3 Ethics and legal mechanism of copyright, privacy, and data security	Legal and ethical considerations regarding data security, privacy protection, and copyright issues.	[13,45,50,51]
	E4 Incentive policies	Government policies, such as subsidies, tax breaks, etc., to promote BDA via enterprises.	[13,16,45,59]
Financial (F)	F1 Extraneous income	Additional benefits or cost reductions from BDA.	[4,32,60]
	F2 Financial capability	Economic ability of stakeholders to apply big data.	[29,32,33,45,50]

3.2. Data Collection and Processing

In order to explore the power and attitude of the stakeholders regarding these factors, a full questionnaire survey was conducted. It consists of two parts: the first part is a background survey, which includes the stakeholders represented, education, experience, BDAC status in their organizations, attitudes towards BDAC, and the number of projects involved in BDA. The second part required participants to identify the relationship between stakeholders and the factors from both the power and attitude perspective. Scoring is completed on a 0–1 method: "1" means the stakeholder will consider/address the factor from the perspectives of attitude and power, respectively, "0" does not.

The questionnaire was sent to the practitioners from the six stakeholders identified above. A snowball sampling approach was applied to collect sufficient data for analysis. A total of 148 questionnaires were obtained after the questionnaire, with too-short filling time and the unsatisfactory occupational background of the respondents being excluded. The respondents represent various stakeholders, such as developer and designer, among six others. The number of valid questionnaires of all stakeholders meets the requirements of SNA [28]. The profile of the respondents is shown in Table 3. In total, 59.11% of respondents had at least four years of experience. A total of 79.05% of survey respondents had been involved in BDA. Notably, only 16.89% of the respondents believe that their organization has a mature approach and experience in BDAC. Meanwhile, 91.89% of respondents believe that BDA is valid in the development of construction enterprises and the implementation of construction projects but has not yet been exploited to its full value. In addition, this study adopted Cronbach's alpha to test the consistency of the evaluation of different stakeholders through SPSS. The results of the consistency test showed the lowest Cronbach's alpha of 0.731 among the six stakeholders under the dimensions of attitude and power. Studies have shown that a Cronbach's alpha greater than 0.7 is associated with high confidence in the questionnaire data and high data consistency [61]. Therefore, the quality and quantity of questionnaire data can be used for social network analysis.

Table 3. Profile of respondents.

Stakeholder	Number	Proportion	Education Background	Number	Proportion
government	27	18.24%	specialist	15	10.34%
developer	51	34.46%	bachelor	76	52.41%
construction contractor	20	13.51%	master	43	29.66%
designer	12	8.11%	doctor	11	7.59%
consultant	22	14.86%			
researcher	16	10.81%			

Table 3. *Cont.*

Years of working	Number	Proportion	Number of BDA projects involved	Number	Proportion
1–3	62	41.89%	none	31	20.95%
4–6	45	30.41%	1–3	52	35.14%
7–9	22	14.86%	4–5	40	27.03%
above 10	19	12.84%	above 6	25	16.89%

3.3. Establishment and Analysis of the Two-Mode SNA Model

The two-mode social network was adopted in this study for data analysis by taking the 15 BDAC factors and 6 stakeholders as two different sets of modes. Referring to previous studies using two-mode network analysis [28,61,62], four steps of two-mode social network establishment and analysis were conducted, including matrix analysis, hierarchical cluster analysis, centrality analysis, and c structure analysis. Firstly, a stakeholder–factor adjacency matrix from the attitude and power perspectives, respectively, was established using the questionnaire results. Referring to previous research, from a specific attribute perspective, a link between a stakeholder group and a factor is retained if at least 80% of the respondents within that group perceive a relationship. Conversely, the link is discarded if this criterion is not met. Based on this, the stakeholder–stakeholder matrix and factor–factor matrix are further developed and analyzed. Secondly, based on the above stakeholder–factor adjacency matrix, a network analysis and visualization are developed using Netminer 4.0 software [18]. Following that, the centrality of the nodes can then be calculated to establish the relative locations of the nodes in the stakeholder–factor network. Subsequently, hierarchical cluster analysis is used to uncover latent relationships between stakeholders and factors, facilitating the identification of the most compatible factors for each stakeholder. Finally, the core–periphery structure of the two-mode network is analyzed to explore the stakeholders in the core position.

4. Results

4.1. Adjacency Matrix Analysis

The stakeholder–factor adjacency matrix is shown in Table 4. The elements of the attitude matrix indicate whether the stakeholders will consider the factors, while elements in the power matrix indicate whether the stakeholders have power over the factors. Based on the adjacency matrix, visual two-mode network graphs were constructed using Netminer 4.0, as shown in Figure 2. The stakeholders are represented by red circular nodes and the factors are blue square nodes, with node sizes proportional to their degree values. The two-mode network exhibits 59 and 43 links in the attitude and power perspectives. All factors are connected to at least one stakeholder, and certain nodes have multiple stakeholder connections, which demonstrates the potential for collaboration and the underlying motivations among the stakeholders.

Table 4. Stakeholder–factor adjacency matrix.

Attitude perspective																
	T1	T2	T3	T4	T5	O1	O2	O3	O4	E1	E2	E3	E4	F1	F2	SUM
S1	0	1	0	0	0	0	1	0	0	1	0	0	0	1	1	5
S2	0	1	0	0	0	1	1	1	1	1	1	0	1	1	1	10
S3	1	1	1	1	1	0	1	1	1	0	1	0	1	1	1	12
S4	0	0	1	1	1	0	0	1	1	1	1	1	0	0	0	8
S5	0	1	0	1	0	1	1	0	1	1	0	0	1	1	1	9
S6	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	13
SUM	2	5	3	4	3	2	4	4	5	5	4	2	4	5	5	

Table 4. *Cont.*

Power perspective															
	T1	T2	T3	T4	T5	O1	O2	O3	O4	E1	E2	E3	E4	F1	F2	SUM
S1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	11
S2	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1	10
S3	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	4
S4	1	0	1	0	1	0	0	1	0	0	0	1	0	1	0	6
S5	1	1	1	1	0	0	0	0	0	0	0	0	1	1	0	6
S6	1	1	0	1	0	1	0	1	0	0	0	1	0	0	0	6
SUM	5	5	5	5	1	3	1	3	2	2	1	3	2	3	2	

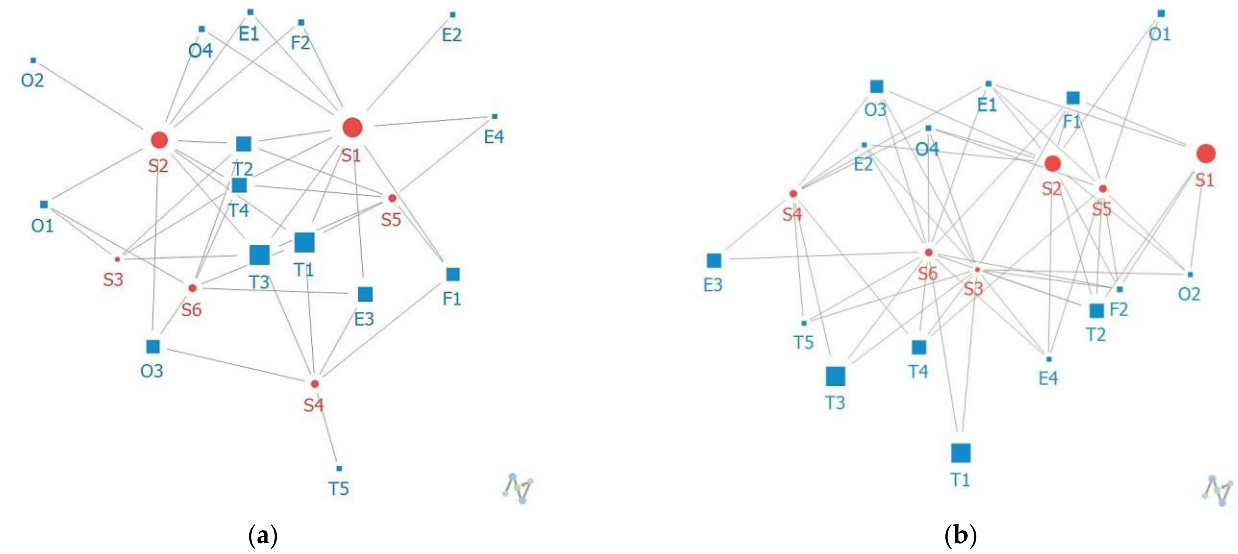


Figure 2. Visualization of stakeholder–factor two-mode network: (**a**) power network; (**b**) attitude network.

Regarding the stakeholders, Table 4 indicates that S6 (researcher) has the highest number of factors (13 factors) to consider in BDCA, followed by S3 (construction contractor). Both of them are concerned about all technology factors. S3 is in charge of the project's construction and, therefore, takes more into account for the technical and equipment aspects of the actual operation. From the power perspective, S1 (government) has the power to address the most factors (11 factors) among the six stakeholders, followed by S2 (developer), who has power over ten factors. Each stakeholder has power over at least three technology factors. In addition, S1 is the only stakeholder that can address all the financial and environmental factors, while S2 can address all the organizational factors. In terms of the number and types of factors, government and developer are the most critical stakeholders, with their collaboration and resource allocation being of paramount importance. Furthermore, each stakeholder can address at least three technical factors, which suggests that the joint influence of stakeholders is mainly on technical factors.

Regarding the factors, T2 (availability of BD facilities), O4 (data-driven culture), E1 (stakeholder willingness to collaborate), F1 (extraneous income), and F2 (financial capability) attracted the most attention according to the attitude matrix. The power matrix illustrates that each of the 15 factors presented in this paper has at least one stakeholder with the power to address them. Regarding the required stakeholders to address the factors, T1 (availability of BD technologies), T3 (construction data quality), and T4 (exemplary projects) can be addressed by five stakeholders, indicating that the common influence of stakeholders is manifested in technology factors. T5 (fragmented nature of construction data), O2 (support from top management), and E2 (standards and guidance) have only one stakeholder with power over them, which indicates that they need to be addressed by specific stakeholders. Among the four categories of factors, environmental and organizational factors have the least stakeholders with power over them, and both financial factors are of concern to the five stakeholders.

The element in the stakeholder–stakeholder adjacency matrix shown in Table 5 indicates the number of factors that the stakeholder pair has the power to address or is commonly concerned about. This number can be viewed as the power or attitude similarity of various stakeholders, implying the possibility of collaboration [62].

Table 5. Stakeholder–stakeholder adjacency matrix.

Attitude Perspective							Power Perspective						
	S1	S2	S3	S4	S5	S6		S1	S2	S3	S4	S5	S6
S1	5						S1	11					
S2	5	9					S2	7	10				
S3	4	7	11				S3	3	4	4			
S4	1	3	5	7			S4	4	3	1	6		
S5	5	8	7	3	9		S5	6	4	3	3	6	
S6	4	7	10	7	7	13	S6	4	5	3	3	3	6

From the attitude perspective, S3 (construction contractor) and S6 (researcher) share common concern over 10 factors including all technology and financial factors. In the meantime, S2 (developer) and S5 (consultant) share a common focus on eight factors, which indicates a convergence of concerns between them in BDAC. From the power perspective, the power similarity between S1 (government) and S2 is the highest of all the stakeholder pairs. Collectively, they can address 46.6% of the factors, followed by S1 and S5, who can jointly address six factors. In summary, the convergence of concerns and similarity of power between S1, S2, and S3 provide motivation and potential for collaboration. Given the prominent roles of S1 and S2 within the network, their collaboration with S3 is indispensable. Conversely, S3 and S4 (designer) only address T3 (construction data quality) together. Furthermore, there are no stakeholder pairs without common solvable factors, which highlights the importance of collaboration among stakeholders.

The factor–factor adjacency matrix can examine the resource similarity of the factors [28]. The element in this matrix reflects the number of stakeholders with the same power over two factors. Coping with multiple factors is challenging for stakeholders due to limited resources. The factor–factor matrix can help stakeholders allocate resources for different factors and make decisions that benefit BDAC [28]. Therefore, this paper only analyzes the factor–factor matrix from the power perspective. The matrix illustrates that there are five factor pairs that have the highest resource similarity, which are T1 and T3, T2 and T3, T1 and T4, T2 and T4, and T3 and T4. These five pairs of factors are all technical factors, which implies that these technology factors have high resource similarity and require the actions of similar stakeholders and stakeholders' capabilities to be focused on these factors. However, there are a total of 17 pairs of factors that cannot be collectively addressed by stakeholder pairs and 40 pairs of factors with extremely low resource similarity, which account for the majority of all factor pairs. This suggests that most factor pairs of BDAC require different stakeholders' actions to tackle.

4.2. Centrality Analysis

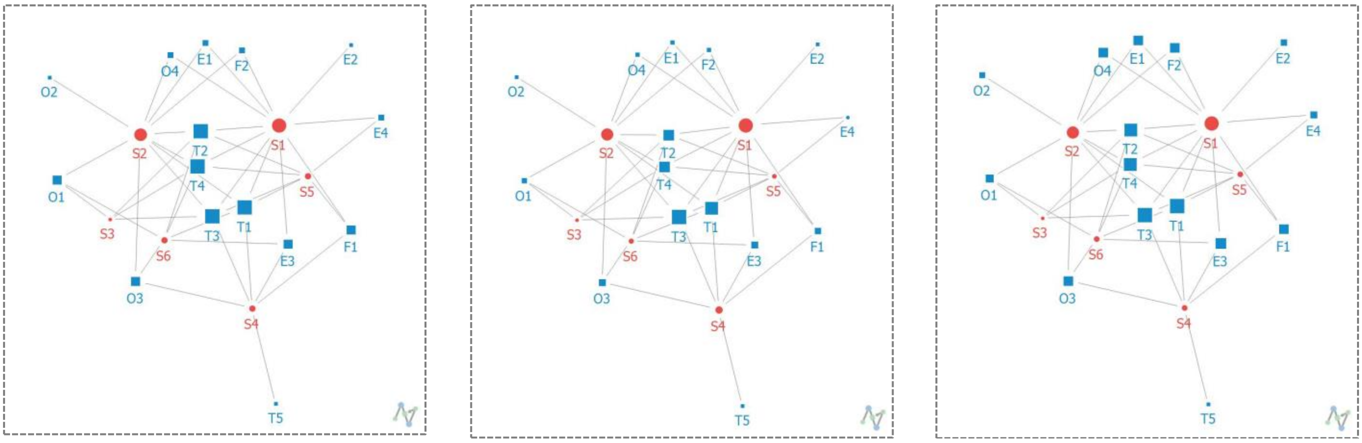
Based on the stakeholder–factor two-mode network, Netminer 4.0 is used to calculate the degree centrality (DC), betweenness centrality (BC), and closeness centrality (CC) for each node. The DC, BC, and CC of the nodes can be utilized to evaluate their relative positions. DC reflects the immediate connectivity or popularity of a node. BC is a measure of a node's strategic position, suggesting its potential to influence or obstruct the flow of information via it. CC measures the distance of a node from other nodes in the social network, reflecting the closeness of its ties. EC is a measure of the influence of a node in the network. [63]. The identified stakeholders and factors with high centralities can be regarded as the most critical. This paper analyzes the above three centrality indicators for both two-mode networks. Taking the power perspective as an example, the calculation results are shown in Tables 6 and 7. According to the calculation results and ranking of each indicator of each factor and stakeholder, the visualized network diagram of DC, BC, and CC in the power perspective is shown in Figure 3.

Table 6. Stakeholder degree values from the power perspective.

Stakeholder	DC	BC	CC	EC
S1 Government	0.733333	0.338862	0.757576	0.558065
S2 Developer	0.666667	0.280883	0.714286	0.517992
S3 Construction Contractor	0.266667	0.020590	0.531915	0.264080
S4 Designer	0.400000	0.145675	0.581395	0.289251
S5 Consultant	0.400000	0.063822	0.581395	0.377236
S6 Researcher	0.400000	0.051983	0.581395	0.352897

Table 7. Factors with the highest degree value in the power perspective.

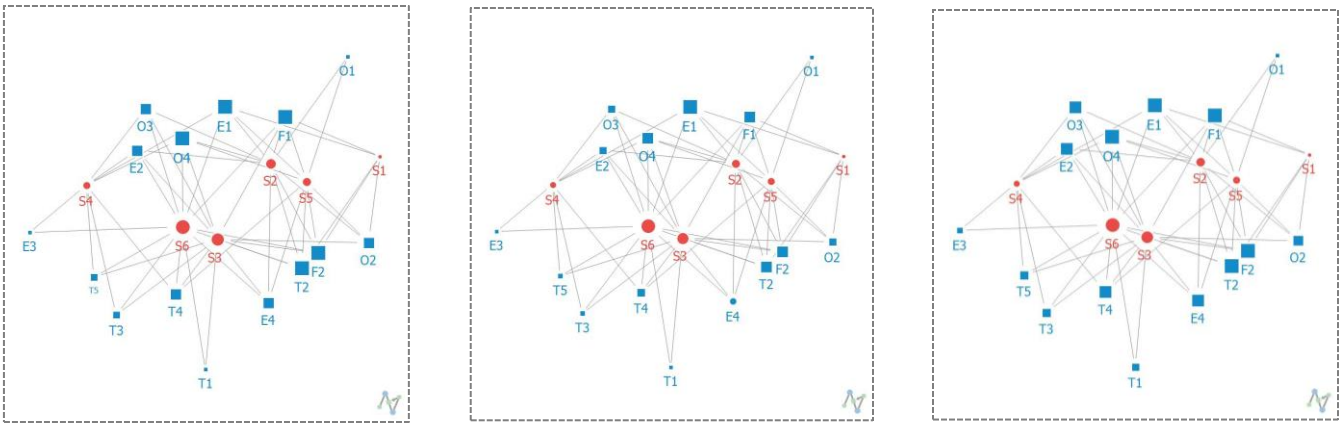
Ranking	Factors	DC	Factors	BC	Factors	CC	Factors	EC
1	T1	0.833333	T3	0.126024	T1	0.944444	T1	0.399038
2	T3	0.833333	T1	0.111482	T3	0.944444	T2	0.394244
3	T4	0.833333	T4	0.083037	T4	0.894737	T4	0.394244
4	T2	0.833333	T2	0.083037	T2	0.894737	T3	0.282124
5	E3	0.500000	E3	0.039641	E3	0.809524	F1	0.233193



(**a**) (**b**) (**c**)

Figure 3. Two-mode networks under the centrality measure (power perspective): (**a**) DC; (**b**) BC; (**c**) CC.

From the perspective of stakeholder power, the government exhibits the highest centrality in all indicators, followed closely by developers. Together, they occupy the highest positions of centrality, exerting the most significant influence on the BDA collaboration network. Both have abundant resources to address numerous factors (DC), are strategically positioned at the network's core (CC), are the most influential and authoritative actors (EC), and significantly impact resource and information exchange (BC). Therefore, it can be concluded that the collaboration network in the context of big data application exhibits a dual-core critical structure, with developers and the government assuming leadership roles in stakeholder collaboration and application activities. Moreover, the high DC, CC, and EC of consulting indicate their potential to influence information exchange and contribute to specific factors, suggesting their capacity for collaboration with both the government and developers. The factors T1, T2, T3, T4, and E3 have a higher DC, which means they have an involvement with a larger number of stakeholders and increased complexity in addressing these factors. The resolution of technical factors requires more stakeholder collaboration, while for E3, a universally accepted legal and ethical safety management protocol should be established to ensure data security and privacy. The remaining indicators, T1, T3, T2, and T4, also have the highest centrality. Therefore, in practical BDCA, emphasis should be placed on developing technical factors, such as fostering collaboration with research institutions, and investing more in technology and infrastructure to enhance application performance. Figure 4 shows the centrality visualization network diagram from the attitude perspective.



(**a**) (**b**) (**c**)

Figure 4. Two-mode networks under the centrality measure (attitude perspective): (**a**) DC; (**b**) BC; (**c**) CC.

From the attitude perspective, researchers have the highest centrality for all four, which suggests that they consider most of the factors in the process of big data application. Therefore, they have a solid need to collaborate with other stakeholders. The factors F1 (extraneous income) and F2 (financial capability) had the highest values of three centrality indicators, which indicates that they have attracted a great deal of interest from the stakeholders and are the focus of attention. In addition, E1 (stakeholder willingness to collaborate) has a higher DC, CC, and EC and occupies an important position, so it should promote the construction of synergistic platforms. O1 (organizational structure) and O4 (data-driven culture) also have a high centrality, and developers should apply their own resources and power to realize the organizational framework required for big data applications as well as the establishment of driving culture.

4.3. Hierarchical Cluster Analysis

The optimal match between stakeholders and influencing factors is obtained through Netminer 4.0, as shown in Table 8. In the case of limited resources, stakeholders should take the lead in addressing or focusing on the factors that best match them.

Table 8. HCA-based stakeholder and factor optimal matching.

Stakeholders	Optimal Matching Factor	
	Attitude Perspective	**Power Perspective**
S1 Government	E4	E1
S2 Developer	O1	O1
S3 Construction Contractor	T4	T3
S4 Designer	T3	T4
S5 Consultant	T2	T2
S6 Research	T1	T1

It can be seen that the primary responsibility of the government is to establish an incentive mechanism and introduce incentive policies to promote the application of big data by other stakeholders, and in this process, the government pays great attention to the stakeholders' willingness to cooperate (E4). For developers, O1 (organizational structure) is their primary task and the most important influencing factor. As the main body of the application of big data in construction, it is crucial to establish the corresponding internal organizational structure. T4 (exemplary projects) is the most matching factor under the power perspective of the designer, which indicates that the designer needs to prioritize the collation of their own past design data and ultimately establish a design database for the design work of other subsequent projects to reduce the risk of the design work of other projects. At the same time, T4 is still the factor of highest concern for construction contractors. The process of construction projects is long and complex, coupled with the overall industrialization and standardization of a low degree. Construction contractors need the support of past successful cases for schedule control and safety management, so they should participate in establishing a construction database to solve their biggest concerns. T3 (construction data quality) is the most matched factor between the designer's attitude perspective and the construction contractor's power perspective. Data quality is the foundation of big data application, and data management should be strengthened to ensure data quality in the design and construction phases. The most matching factor for the researcher is T1 (availability of BD technologies). It is time-consuming and risky for enterprises in the construction industry to independently complete the development and application of technologies, so the research structure is taken as a cooperative object to share the risks and benefits. Therefore, the role of the research structure in the application of big data in the construction industry is to provide relevant technical support.

4.4. Core–Periphery Structure of the Stakeholder–Factor Network

This paper uses the core–periphery structure to identify the key stakeholders who can address the critical factors and facilitate the cooperation of other stakeholders. Therefore, only the core–periphery structure from the power perspective will be discussed. The results of the density matrix obtained from the analysis show that the final fitness of the matrix is 0.674, indicating that the structure of the stakeholder–factor network fits the ideal core–periphery structure. The density of the core-to-core ties is 1.000. This indicates a strong correlation between stakeholders and factors at the core of the power perspective. The densities of the core stakeholders to periphery factors and the periphery stakeholders to core factors are 0.469 and 0.700, which indicate that the connections are loose. Moreover, the density of the periphery–periphery matrix is 0.290, which is significantly lower than that of the core elements. Therefore, stakeholder–factor networks show a core–periphery structure.

The core stakeholders and factors are identified in Table 9, illustrating three core stakeholders and four core factors. Regarding the core factors, T1 (availability of BD technologies), T2 (availability of BD facilities), T3 (construction data quality), and T4 (exemplary projects), with limited resources, stakeholders can prioritize addressing them. S1 (government), S2 (developers), and S5 (consultant) are the core stakeholders, and it is crucial to cultivate a cooperative relationship between them. They perform important coordinating responsibilities. As seen from the density matrix results, all core factors can be addressed by the core stakeholders. If the three core stakeholders can collaborate, they can address the most factors in BDAC and weaken the impact of peripheral factors. The cooperation among them can also facilitate the better collaboration of peripheral stakeholders. The exchange of information among these key stakeholders is important, as it may lead to the establishment of common values, attitudes, and interests toward BDAC [64].

Table 9. Core–periphery structure model of power stakeholder–factor network.

	T1	T2	T3	T4	T5	O1	O2	O3	O4	E1	E2	E3	E4	F1	F2
S1	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1
S2	1	1	1	1	0	1	1	1	1	1	0	0	0	0	1
S5	1	1	1	1	0	0	0	0	0	0	0	0	1	1	0
S3	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0
S4	1	0	1	0	1	0	0	1	0	0	0	1	0	1	0
S6	1	1	0	1	0	1	0	1	0	0	0	1	0	0	0

5. Discussion

As an industry characterized by fragmentation and conservatism, the construction sector necessitates collaborative efforts among stakeholders to form a relatively stable innovation network, facilitating the widespread adoption of innovative technologies [65]. This paper used a two-mode network with six stakeholders and 15 factors to find the best path for collaboration among stakeholders. The findings complement previous studies by demonstrating the power and attitudes of stakeholders towards factors based on a two-mode social network analysis. The key findings include the following: (1) Technical factors are fundamental to BDAC, involving every stakeholder, and the results of the study show that they receive more attention and need to be addressed by all stakeholder groups due to their complexity. (2) Many factors require specialized stakeholders to address them, and each stakeholder's influence is focused on different categories of factors. Due to the low resource similarity of factors and low power similarity of stakeholders, all stakeholders should be involved in the collaboration. (3) The fragmented nature of construction data is a tricky obstacle that can be addressed through stakeholder collaboration and the establishment of standards for construction data. (4) The obvious prominence of developers and government and the apparent core–periphery structure of the network illustrate the necessity for developers and government to lead BDA in the construction industry. Thus, construction data need to be standardized through all stakeholder efforts. Therefore, based on the results of the network analysis, in order to rationally allocate the limited resources of each stakeholder and clarify the focus of responsibility, a collaborative network for the application of big data in construction is established.

As shown in Figure 5, the government and developer, as the most critical stakeholders, are firstly in charge of the environmental and financial factors (government) and organizational factors (developer) according to their capabilities, respectively. For example, the government implements appropriate policies to motivate other stakeholders to apply BD, and develops standardization manuals for fragmented data in the construction industry. The developers, as the main participants throughout the project lifecycle from the initiation to the delivery and even the post-maintenance, are connected to each participant, enhance the organizational structure, and cultivate data-driven culture. Due to the high power similarity among the six stakeholders, the technical factors serve as the focus of attention and influence, requiring joint efforts from all parties. Secondly, based on the findings of the core–periphery structure, the core stakeholders need to work closely with each other, so the consultant should focus on information exchange and feedback with the developer and government. Between the three core stakeholders and other peripheral stakeholders, the motivation and facilitation of the core stakeholders inspires the peripheral stakeholders to join them in promoting BDCA. Meanwhile, the cooperation and feedback of the peripheral stakeholders also contributes to refining the external and internal conditions created by the core stakeholders, enhancing overall efficiency. Lastly, considering the complexity of inter-organizational relationships and inefficient information flow in the construction industry, conventional communication methods are inadequate for digital transformation. To facilitate real-time collaboration, a collaborative platform is necessary to enable information integration, resource integration, and management integration among participants, strengthening stakeholder collaboration.

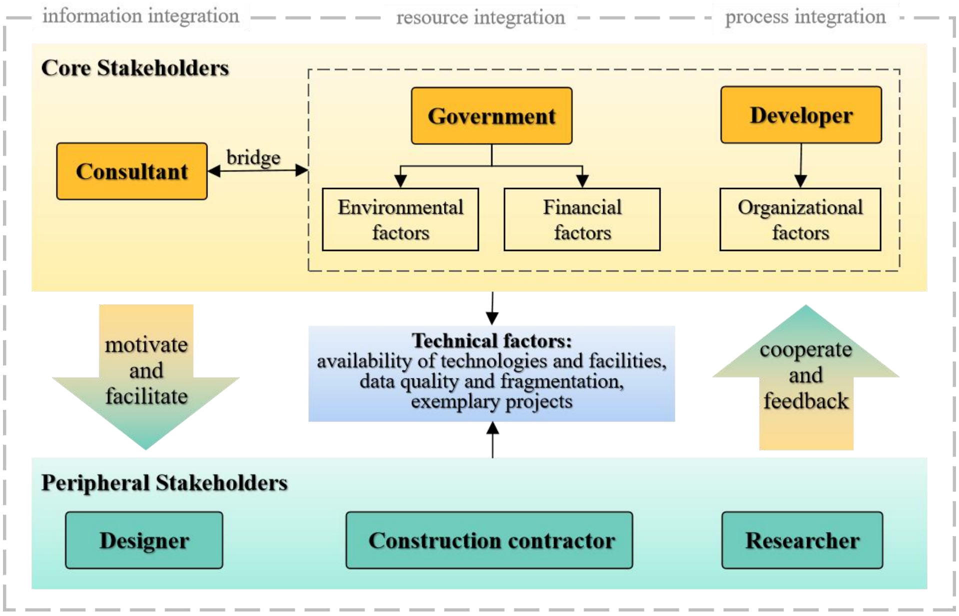


Figure 5. Stakeholder collaboration model structure.

6. Conclusions

Although BDAC is regarded as an inevitable trend, it is still in a preliminary stage. A comprehensive stakeholder collaboration network is essential to facilitate the development of BDAC. In this study, a two-mode social network was established through a literature review and expert interviews, and three adjacency matrices, network centrality, HCA, and core–periphery structural analysis were conducted. These analyses identify the most influential factors and stakeholders. For the influencing factors, stakeholders exhibit high power similarity in technical factors, indicating the potential for collaboration and motivation. Economic factors and collaboration willingness are key areas of interest. In terms of stakeholders, the government, developers, and consultants emerge as core players with a tendency to actively collaborate in addressing central influencing factors. These three parties should establish collaborative relationships to jointly promote BDCA. The government assumes a leading role by creating an external environment, including implementing incentive policies, establishing reward and punishment mechanisms, and refining industry regulations and laws. Developers, as the primary actors in BDA, should enhance their organizational structures, augment human resources, formulate strategic plans, and foster a relevant organizational culture. Finally, this paper establishes a stakeholder collaboration model centered on the government–developer–consultant relationship based on the two-mode network analysis. It provides strategic recommendations to achieve long-term and effective collaborative relationships among stakeholders.

This study explores the associative relationships between stakeholders and factors under the dual perspectives of attitude and power, addressing the gap in previous research that predominantly focused on factors while neglecting stakeholders. This research has important theoretical and practical significance. Theoretically, it provides a deeper understanding of the internal action mechanism and influence transmission path that impact the application of big data in the construction industry. By emphasizing the role of stakeholders, we offer a more comprehensive framework for future research to explore the collaboration of stakeholders. Practically, this study clarifies the stakeholder collaboration relationships and management priorities in BDCA, which provides foundations for decision making, resource allocation, and responsibility assignment in practical scenarios involving stakeholders. This understanding can help stakeholders prioritize critical issues under limited resources and enhance the efficiency of collaboration. The methodology of exploring associative relationships between stakeholders and factors through two-mode social networks is generalizable to other construction markets with good applicability. Despite all the above contributions, this study still has the following limitations. First of all, the 15 influencing factors are only the most important ones proposed according to the literature and expert interviews, which cannot reflect all the factors of BDCA. In addition, since the SNA is constructed based on expert experience through questionnaires, subjectivity cannot be avoided to some extent. Finally, this study did not delve into the specific collaboration mechanisms among stakeholders or incentive schemes of the government. Future research could explore these aspects more profoundly, or more node attributes, such as the type of construction project, could be considered in SNA.

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Data Availability Statement: The original data for this paper were obtained from 148 questionnaires. The original data that support the findings of this study are available from the first author, [Yali Wang], upon reasonable request. The authors confirm that data based on the results of the questionnaire and used for network analysis are provided in the article to support the findings of this paper.

Conflicts of Interest: Hao Wang, Qinglin Meng, and Yuwei Zhai are employees of Powerchina Zhongnan Engineering Corporation Limited. Their employment did not exert any influence on the results or conclusions of this study.

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