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Towards an Integrated Framework for Information Exchange Network of Construction Projects

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Abstract: The application of building information modeling (BIM) disrupts the interaction between individuals and industry organizations from time and spatial dimensions. However, the temporal dimension of interaction is usually a neglected factor in the application of social network analysis (SNA) when studying the project communication networks. Additionally, the social incorporation of BIM enables full collaboration across multiple disciplines and stakeholders, which calls for multi-dimensional research agendas and practice of different network models. To fill the gap, this study aims to develop an integrated framework to guide the analysis of information exchange in construction projects. According to the findings, three network models can be used for network analysis at the industry, project and individual levels. It is worth noting that the majority of recent attention about the project communication networks has been focused on industry and project levels. The network analysis at the individual level is under-researched so we actively explore how to extend the scope of the network analysis from the project and industry level to the individual level. An ego network model was thus proposed to explore the project communication networks at the individual level, where the network indices were derived. The outputs implied that the proposed model has the potential to explore the ego-centric network in the construction projects.

Keywords: information exchange; social network analysis (SNA); building information modeling (BIM); framework; construction projects

Citation: Yang, Y.; Liu, X.; Xie, H.; Zhang, Z. Towards an Integrated Framework for Information Exchange Network of Construction Projects. *Buildings* **2023**, *13*, 763. https://doi.org/10.3390/buildings13030763

Academic Editors: Daniotti Bruno and Osama Abudayyeh

Received: 21 January 2023
Revised: 7 March 2023
Accepted: 11 March 2023
Published: 14 March 2023

1. Introduction

The construction industry is characterized by its fragmented and project-based nature [1], in which multiple stakeholders mostly rely on project-specific and temporary networks to communicate and exchange information [2]. The large volume of information generated across organizational divisions thus poses a significant challenge for project management [3]. One potential approach to analyzing the interactions is to apply network theory and its commonly used analytic instrument, social network analysis (SNA) [4]. With the aid of the SNA, the information exchange network can be visualized to identify the key positions, information routes and information opportunities [5]. SNA is a mathematical technique for empirically investigating the structure and evolution of information exchange networks within a project or across projects. However, the temporal dimension of interaction is usually a neglected factor in the application of SNA when studying the project communication networks [2], and how collaboration within a construction project evolves over time remains largely unexplored [6]. It seems that the potential of SNA to investigate information exchange of construction projects is still far from exhausted.

Construction projects are becoming increasingly complex, which has led to intricate and dynamic relationships [7]. In addition to the relationships within the project, the interactions across the projects will gradually form a more complex relationships network at the industry level. However, in the extant literature, previous studies of project communication networks have mainly been focused on specific projects [8], or the collaborative networks among multiple organizations from a macro network perspective [9]. It seems that there is a lack of network research in construction projects management (CPM) at the individual level. Given its interdisciplinary and inter-organizational nature, the application of building information modeling (BIM) facilitates information exchange across project phases and organizational boundaries [10]. As a systemic innovation, the implementation of BIM in construction projects generally involves the participation of multiple organizations. Although previous studies have mentioned the phenomenon of BIM-centered clustering, the lack of data and an ingenious research design has hindered further research [4]. It is necessary to extend the scope of network analysis from the project and industry level to the individual level. The application of BIM disrupts the interaction between individuals and industry organizations from time and spatial dimensions. However, the temporal dimension of interaction is usually a neglected factor in the application of SNA to study the project communication networks. Additionally, the social incorporation of BIM enables full collaboration across multiple disciplines and stakeholders, which calls for multi-dimensional research agendas and practice of different network models.

Therefore, network research in construction projects needs to take into account the changes that occur in the interactions, as well as the multi-level nature of the network boundary. This paper aims to develop an integrated framework to guide the analysis of information exchange network in construction projects, which is targeted to address the above issues. This is a significant gap in the existing knowledge and represents the first time that such a framework has been proposed. The remainder of the paper is structured as follows. The next section is dedicated to providing a literature review and knowledge discovery. Section 3 illustrates the methodology used in the study. This is followed by a detailed description of a proposed framework for systematizing the network models for CPM research. Section 5 illustrates the metrics that can be used to identify the characteristics of ego-centric network. Finally, Section 6 concludes the study by summarizing the findings, outlining implications, and pointing out the limitations of the study.

2. Literature Review and Knowledge Discovery

2.1. Information Exchange Network in Construction Projects

Information exchange in construction projects is an ongoing and complicated process, which requires the participation of multiple stakeholders for the input, output, and transmission of information in the form of complex networks of intra- and inter-organizational relationships. Multi-disciplinary participants enter, interact, and leave the network at different project phases when there is a need for information interaction [11]. In addition, the temporal nature of the project communication networks, such as duration and time order, adds to the dynamism of project communication networks [2].

The delivery of a construction project generally requires the effective collaboration of various organizations from different disciplines [8]. Yang et al. [12] identified the factors influencing information exchange from three perspectives: interpersonal, intra-organizational, and inter-organizational. With the widespread use of BIM in construction projects, there is a growing interest in analyzing BIM-based construction networks (BbCNs) [13,14]. Zhang and Ashur [15] analyzed the structural properties of BbCNs at three different levels: macro-level (the whole network), meso-level (the subset of nodes), and micro-level (the nodes and links). Cao, Li, Wang, Luo, Yang, and Tan [8] reveal that the characteristics of the network at the macro level are significantly correlated with those at the micro level. Studies on network dynamics tend to believe that information exchange networks are complex adaptive systems, and the evolution of their macro-structural characteristics is driven by the forces operating at the micro-level [8]. However, most of the analyses focused on the structural properties of the network at the macro-level, while the network structure at the meso and micro levels have not been systematically investigated [16]. At the macro-level, the current research mainly uses the whole network due to its ability to reveal the network structure and explore the impact of the structure on the actors within it [17–19]. However, the whole network has some limitations, such as data-driven and case-based [20], which makes the study usually limited to the network analysis and may neglect the analysis of the project performance.

Lu et al. [21] categorized the network analysis as qualitative or quantitative approaches. Qualitative SNA often uses case studies and interviewed-based data, while quantitative SNA usually involves secondary data or surveys of participants and their relationships. Zheng et al. [22] suggested considering a multi-dimensional research design in SNA due to the interactions between the external and internal network cores being two-way. Most SNA-based research was conducted through a case study or multiple case studies. However, single SNA case studies are restricted by capturing the evolving and emergent nature of information exchange networks. This leads to a call for more longitudinal studies that examine information exchange networks at multiple points of time in its evolution [21]. For example, Pirzadeh and Lingard [2] adopted longitudinal SNA to examine the changes in network density over time; Wang, Zhang, and Lu [4] used longitudinal SNA to compare the changes of relationship networks across work stages to identify the communication issues between the actors.

In terms of longitudinal studies, longitudinal single case studies are abundant in the existing literature, but the longitudinal across-project case studies, multilevel studies, and longitudinal quantitative studies have not received sufficient attention. Thus, more discussion of qualitative studies based on interviews, quantitative studies based on primary or archival data, and mixed-methods studies based on a combination of qualitative and quantitative surveys are needed [23].

2.2. SNA Used in Construction Projects Management (CPM) Research

SNA has been widely used for project communication networks over the past two decades [24], which has mostly been used to analyze static networks by taking a snapshot of the social interactions at a particular point in time [25] or aggregated networks over a period of time [26]. This approach assumes some level of stability in a project communication network over time [2]. Since the frequency of information exchange may fluctuate over the project phases, there is a need to consider the dynamics of the network [27]. Additionally, the project communication network constantly expands by the addition of new actors and technology [28]. The project communication network may change over time, and thus, assuming that the network structure remains unchanged, may not match the actual situation [26].

SNA can be divided into whole network analysis and ego network analysis (or personal network analysis) [29]. A whole network can be used to analyze the relationships among all actors within a group, which has been widely used for project communication networks due to its ability to reveal the network structure and explore the impact of the network structure on the actors within it [17–19]. Most of SNA are data-driven and case-based [20]. Ego-centric network, also known as personal network, is a network of interconnected individuals [30]. By studying the parameters of the personal network, such as the network size, heterogeneity, homogeneity, and composition, it is possible to gain a more comprehensive understanding of the individual's behaviors in the network [31,32]. In order to explore structural properties of social networks at the micro-level, Arnaboldi, Conti, Gala, Passarella, and Pezzoni [16] used ego network model to investigate a direct impact of tie strength and ego network circles on the information diffusion. The information exchange among key actors has a significant impact on knowledge creation and innovation. Xue et al. [33] applied ego network analysis to identify the key members and analyzed the roles and functions of these key members in the construction innovation.

2.3. BIM–Based Construction Networks (BbCNs) and Ego-Centered Analysis

In a multi-participant and multi-disciplinary working environment, BIM aims to facilitate information exchange and communication among stakeholders over the project lifecycle. The introduction of BIM technology changes the structure of project communication network by making it looser and flatter [21]. Thanks to the contributions of network studies from other disciplines (e.g., sociology, anthropology, and information technology), some scholars attempt to explore BbCNs (e.g., Zhang and Ashur [15]; Lu, Xu and Söderlund [21]). For example, Du et al. [34] indicated that BbCNs have more direct connections and shorter paths among the nodes, making the interpersonal information exchange easier and faster. Due to the wide application of BIM technology in the construction projects over time, Cao, Li, Wang, Luo, Yang, and Tan [8] believe that the position of key actors (e.g., BIM manager) will become more centrally located in project communication networks. The application of BIM may produce distinct network structures in construction projects [35], in which prominent brokerage positions will be occupied by the new disciplines, e.g., the BIM manager [36]. Participants will form new project communication networks centered on the key actors (e.g., BIM manager). Effective application of BIM requires more direct contact between the central actor (e.g., BIM manager) and other participants, so ego-centered analysis was considered to be more suitable for BbCNs [37]. However, few studies have investigated the ego-centric network in CPM research.

Although previous studies have mentioned the phenomenon of BIM-centered clustering, the lack of data and an ingenious research design has hindered further research [4]. For example, Yang, Shen, Ho, Drew, and Xue [12] suggested that the issue of insufficient data may arise due to the fact that anonymity cannot be assured when collecting data. Du, Zhao, Issa, and Singh [34] identified that the available data may not be sufficient for an exclusive conclusion about the impacts of BIM on project networks and it is difficult to replicate the same analysis without sufficient data supported. As stated by Leigh Allison and Jessica Kaminsky [38], data quality is the key limitation of social network research.

An ego network can be described as a portion of a social network formed of a given individual (referred to as the ego), and the other members with whom the ego has a social link (referred to as the alters) [16]. As depicted in Figure 1, the alters are usually arranged in a series of circles based on the strength of their social ties, and the ego is located at the center of the series of concentric circles. An ego-centered model is considered to be suitable for analyzing the networks centered on a target population with links extending to more than one social structure [39]. A new coalition formed around a target population would reshape the structure of the project communication networks. Lam et al. [40] suggested that the target populations with different backgrounds could give rise to different structure of information exchange network. Unfortunately, ego-centered analysis has seldom been used in CPM studies.

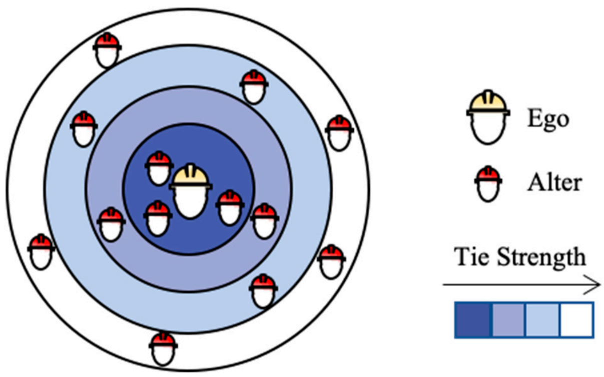


Figure 1. Ego network structure.

2.4. Knowledge Discovery

The application of BIM disrupts the interaction between individuals and industry organizations from time and spatial dimensions. However, the temporal dimension of interaction is usually a neglected factor in the application of SNA to study the project communication networks. Additionally, the social incorporation of BIM enables full collaboration across multiple disciplines and stakeholders, which may open a unique multilayered dimension for the network analysis. Social and technological changes in the construction industry calls for multi-dimensional research agendas and practice of different network models. Based on extensive literature reviews and interviews with experts, network range, network level, and research design were proposed as three dimensions in network research for construction projects. As illustrated in Figure 2, studies of the project communication networks need to take into account the multilayered nature of the network boundary [4].

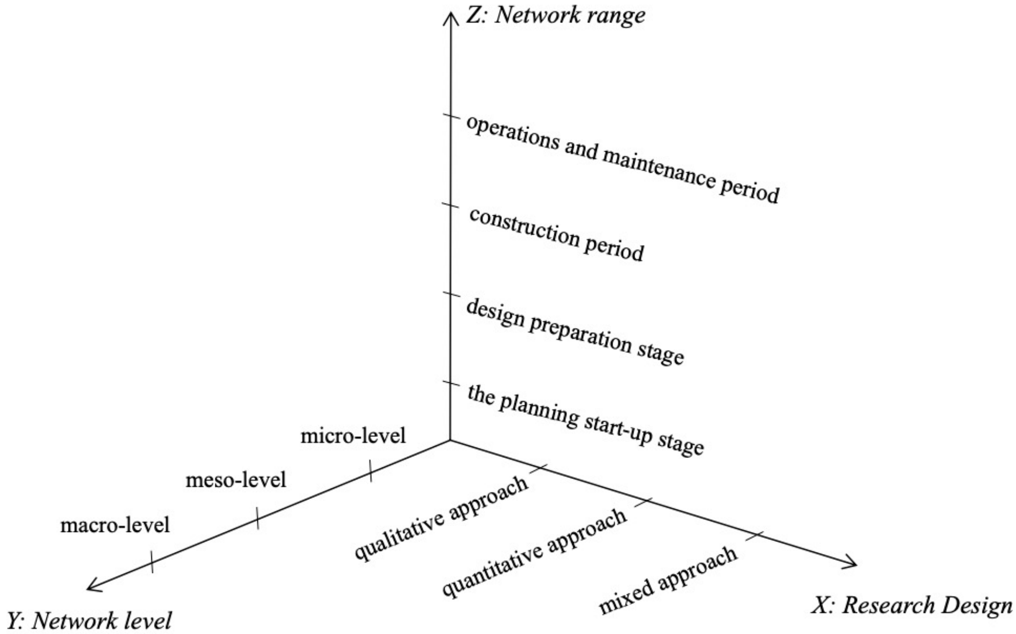


Figure 2. Multiple dimensions in network research for construction projects.

The question now is whether there are network models available that can be used for the multi-dimensional network analysis shown in Figure 2. An in-depth understanding of the network analysis used in current research of project communication networks could be a breakthrough in addressing the above issue. From the perspective of information exchange, research on the project communication networks can be integrated from the industry, project, and individual levels. SNA has so far centered on the analysis of intra- and inter-organizational relationships. Intra-organizational studies were primarily applied at the individual or group level [22]. Most of the inter-organizational relationships have been investigated as project-level networks within a specific construction project [8]. As new projects are initiated, the new project communication networks will continuously be formed at the project level. The collaborative relationships between industry organizations in different project contexts will also incrementally form more complex communication networks at the industry level [9]. Based on extensive literature reviews, it is discovered that the majority of recent attention has been focused on specific projects, or the collaborative networks among multiple organizations [9]. However, there is a lack of network research in CPM at the individual level.

3. Methodology

As suggested by Fellows and Liu [41], a triangulation research strategy combining literature review, theoretical analysis, and interviews is adopted for this research. The study started with an extensive literature review to capture background knowledge and identify the limitations of the SNA used in the state-of-the-art CPM studies. The multiple dimensions in network research for construction projects are explored as knowledge discovery. Guided by this, an integrated framework is developed from the industry, project and individual levels, including introducing an ego network model to address the new challenge from the BIM-centric clustering. Based on the theoretical analysis, the network metrics of Model 3 are derived, and a case study was used to illustrate the usefulness of Model 3. The interviews were found useful in acquiring a deep understanding of the current network analysis in CPM and collecting data for model validation. The case study was also reviewed and discussed by the interviewees. In order to provide empirical evidence towards the theoretical explanations of network analysis, focus group meetings were conducted with the experts to collect insights and feedback from the interviewees, then the research results will be further revised and improved after the completion of each section. Figure 3 illustrates the proposed research process.

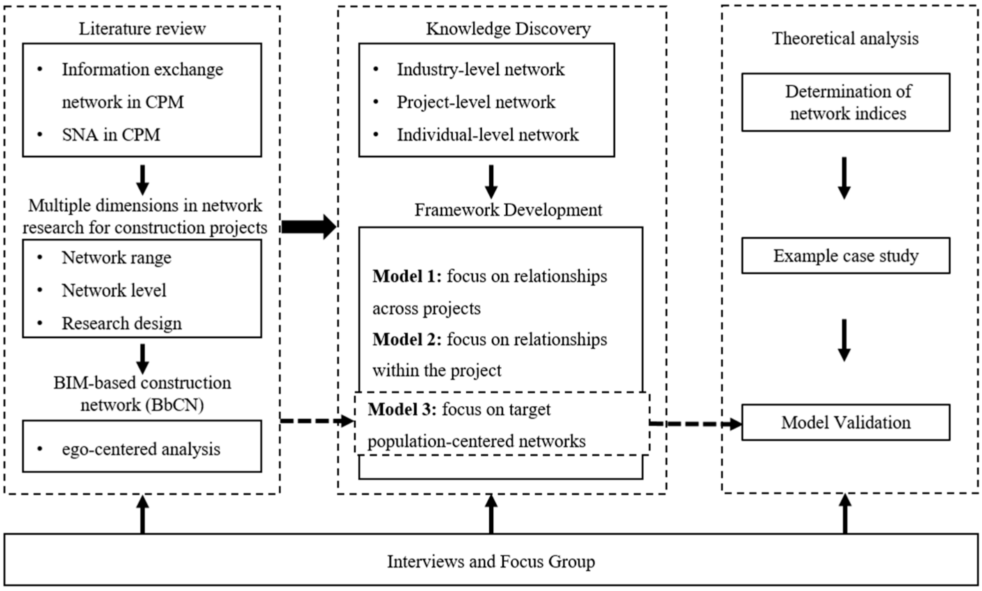


Figure 3. The methodology roadmap.

3.1. Literature Review

Literature review is regarded as a useful methodology to gain an in-depth understanding of a research topic [42]. Following the literature review, a knowledge discovery approach was used to analyze the existing literature, identify research gaps, and provide new insights. Firstly, from the initial literature survey, certain words were used to retrieve the relevant papers in CPM research, such as social network, SNA, communication network, project network, etc. The core collection database of Scopus and Web of Science was searched for relevant publications which were published from 2000 to 2021. According to the first criterion, a total of 107 papers were retrieved. Secondly, papers not written in English, book reviews, editorials, and conference papers were eliminated, then a total of 86 papers were reviewed. Thirdly, 35 papers in peer-reviewed English journals were included for the review with considering their impact positions in CPM research in terms of SCImago Journal Rank and H-index. Then, 17 papers from other research fields about ego-centered networks were added. To decrease potential bias during the selection of target papers, the contents of each paper were screened by different authors to identify the ones suitable for this study. After the whole elimination process, a total of 52 papers were retained for the review.

The knowledge discovery in this paper mainly included the following four parts: (1) to identify the limitations of the network analysis in current CPM research; (2) to identify the multiple dimensions in network research for construction projects; (3) to classify the network analysis based on the relationships within the project or across projects, and static or longitudinal analysis; (4) to identify the potential of ego-centric model for analyzing the networks centered on a target population (e.g., BIM manager) considering the characteristics of the project communication networks.

3.2. Theoretical Analysis

As mentioned above, ego-centered analysis was considered to be more suitable for the BbCNs, but it has been seldom used in CPM studies before. It is necessary to construct the measurement indicators of ego-centered analysis considering the characteristics of the project communication networks. Based on the theoretical analysis of the ego-centered models, the network metrics are derived to understand the characteristics of the ego-centric clustering in construction projects resulting from the application of BIM technology.

The theoretical analysis in this paper mainly include the following three parts: (1) to identify the limitations of Model 1, 2 used in current CPM research; (2) to identify the potential of ego-centric model for analyzing the networks centered on a target population (e.g., BIM manager) by comparing the two commonly used network models of SNA, i.e., the whole network and ego-centered network; (3) to derive the network metrics suitable for analyzing the networks centered on a target population (i.e., Model 3) considering the characteristics of the project communication networks.

3.3. Interviews and Focus Group

Semi-structured interviews were conducted to collect more detailed information about interviewees' experiences and perceptions on the network analysis in CPM, with representatives distributed among four key stakeholders: (1) research institution; (2) design company; (3) construction company, and (4) software company. The research team prepared in advance, aiming to discover the following in the interviews: (1) the limitations of SNA used in the current CPM research; (2) the feasibility of ego-centered analysis used in CPM research; (3) the impact of BIM application on the network analysis; (4) recommendations for the network analysis in CPM research. Yang et al. [43] indicated that interviews and focus groups can be used to enhance participation of the practicing community and researchers in the system development process, leading to increased credibility and acceptability of the research results. Credibility will be established and enhanced continuously during the whole research process by involving a panel of expert practitioners at each critical stage of framework development.

4. Framework of Network Models in Construction Projects

While information interactions within or between organizations have mostly been analyzed as project-level networks, there is a growing interest in investigating how organizations interact with each other across projects from an industry level [8]. According to Figure 2, studies of information exchange network in construction projects need to take into account the multilayered nature of the network boundary and dynamic features across the project phases or across the projects. A framework shown in Figure 4 is thus proposed to integrate the network analysis from the industry, project, and individual levels, in which three network models are derived to measure and analyze the information exchange networks involved. Industry-level research focuses on investigating how industry organizations interact with each other across projects within the construction industry; project-level research focuses on the interpersonal, intra-organizational, and inter-organizational relationships within individual projects; individual-level research focuses on target population-centered networks. Recently, researchers have started examining the impacts of BIM implementation on construction projects, which can be achieved by comparing the differences between the BIM and non-BIM projects with respect to project networks [34]. The appropriate network model is determined based on the purpose of the study and the available data.

As shown in the right side of Figure 4, three network models serve for the information exchange networks from the industry, project and individual levels, which can be divided into cross-sectional and longitudinal ones. Cross-sectional studies are often used to analyze the static structures of construction communication networks over a particular time period, while longitudinal studies are used to explore how the network structures evolve over time [22]. Longitudinal studies can be understood as a collection of cross-sectional studies conducted in a chronological order, which can employ both visual and statistical approaches.

Visual analyses depend on the observation of the network graphs, while statistical analysis relies on the network metrics [21].

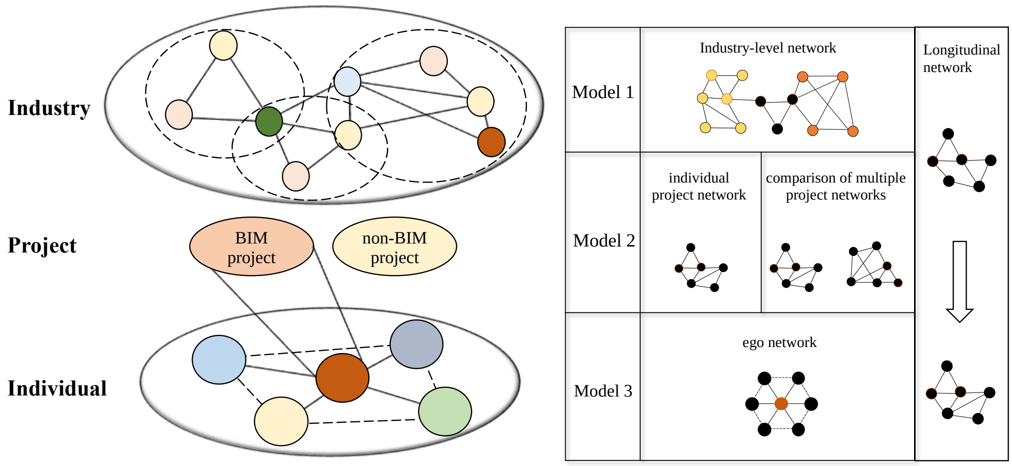


Figure 4. Framework of network models for CPM research.

The following section describes the three models in detail.

- Model 1—Key features:
    1. With the initiation of different construction projects in the industry, industry organizations will gradually agglomerate into more complex project communication networks at the industry level based on their project-specific partnerships [8];
    2. Model 1 can be used to analyze the industry-level network, particularly the interfirm networks, which aggregate collaborative relationships in different project contexts into the macro networks at the industry level to examine how industry organizations interact with each other across different projects [9];
    3. Industry-level networks are typically more dynamic than those at the project level which characterize collaborative relationships within individual projects [8].

While extant research on industry-level networks focused on exploring the static structures among different industry organizations within a particular time period [9], there is also a growing interest in investigating the mechanisms of how the collaborative structures evolve over time. For example, Cao, Li, Wang, Luo, Yang, and Tan [8] empirically investigated how industry organizations interact with each other across projects within the construction industry.

- Model 2—Key features:
    1. Most of the interpersonal or inter-organizational relationships have been analyzed as project-level networks within individual construction projects. Once the project-level network is established, interrelationships between stakeholders and tie strength at a given stage can be explored [7];
    2. There are two different studies of project-level networks: (1) individual project network, e.g., Trach and Bushuyev [44] analyzed the flow of information between project participants within the project network, and (2) comparison of multiple project networks, e.g., Du, Zhao, Issa, and Singh [34] compared the differences between the BIM and non-BIM projects with respect to project-level networks;
    3. Model 2 can be used to analyze the project-level networks, especially intra-project networks, which characterize interpersonal or inter-organizational relationships within an individual construction project [45];
    4. The analysis of Model 2 includes the organizations (nodes) and their relationships (ties), which focuses on the structures of the entire network [46];
    5. While Model 2 has mostly been used to analyze the static networks by taking a snapshot of social interactions at a particular point in time [2], there is also a

growing interest in investigating the dynamic changes in the structure of project communication networks. For example, Pirzadeh and Lingard [2] explored the dynamic nature of social interactions between project participants in construction projects; Lu, Xu, and Söderlund [21] investigated the effects of BIM on projects using a longitudinal SNA with empirical data stemmed from two comparable construction projects.

Some limitations of Model 2 may affect its application. Firstly, the findings from a specific project may not be generalized to other projects. Secondly, mapping a project-network needs the data from each participant of the project, which requires a large amount of data and an ingenious research design.

- Model 3—Key features:
  1. Model 3 can be used to analyze the ego-centric clustering in construction projects resulting from the application of Information and communication technology (ICT) (e.g., BIM);
  2. Model 3 uses the ego network to gain a more comprehensive understanding of the focal actor's behavior;
  3. In Model 3, data are typically collected by drawing anonymous respondents from a large population and collecting information about each of their ego networks [47];
  4. Model 3 can be used to analyze the role and functions of key actors in the network. For example, Xue, Zhang, Wang, Fan, Yang, and Dai [33] identified three key actors in construction innovation network, and analyzed their different functions in the innovation process;
  5. Model 3 can also be used to examine the impact of the focal actor on the project communication networks when the focus of study is a target population [48], which has been widely used in sociology and psychology [49,50].

As mentioned above, the static analysis of Model 1 and 2 has been validated in previous studies. However, there are few studies on longitudinal analysis of Model 1 and 2 due to lack of empirical data from construction projects. The ego-centric analysis of Model 3 has been seldom used in CPM studies, and the network metrics of Model 3 will be derived in the next section.

5. Construction of Model 3

The ego-centric network model has been widely used in sociology and psychology. As discussed above, Model 3 can be used to analyze the ego-centric clustering in construction projects resulting from the application of BIM technology. Figure 5 graphically displays the project communication network of Model 3. As the BIM manager acts as a communication bridge for information exchange, a basic community is formed by a cluster of actors (e.g., contractors, architects) who are in direct contact with the focal actor (e.g., BIM manager). In BbCNs, such a cluster represents a team, in which the members frequently exchange information with each other, while they do so less with persons outside the team [37]. The clustering network presents the characteristics of communication and information flow among the construction project actors. The graph shows the links of the focal actor (e.g., BIM manager) with the alters (the other actors with whom the ego has a direct social connection).

To explore the ego-centric clustering in construction projects, three research assumptions can be proposed as: (1) individuals are always associated with people who are similar to themselves in key attributes, such as political views [51]; (2) the more heterogeneous an individual's network is, the more diverse its social network and the more complex its network structure [52]; (3) individuals' perceptions of the network relationships they are in may influence their behaviors [53]. The network type, the network components, and the network indices are determined in the following section.

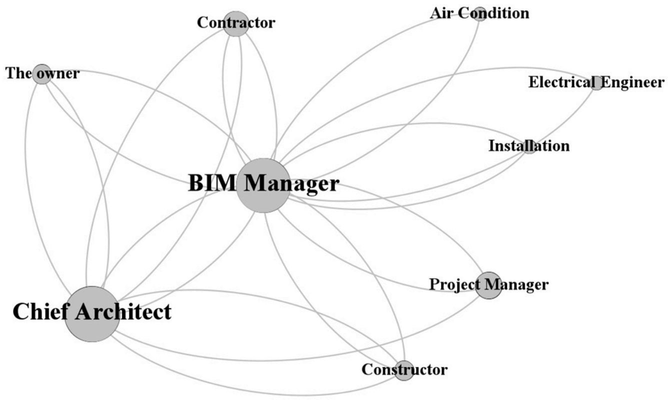


Figure 5. A graphical presentation of Model 3.

5.1. The Network Type

The ego network has some limitations in analyzing the structure of the relational network [54], e.g., some indices of the ego network can be invalid in the analysis of an individual's position in the network. And the indicators of the whole network can be introduced to detect the structural disparities of the information exchange networks before and after the application of BIM. Therefore, the ego network and the whole network can be used and complement each other in Model 3.

5.2. Network Components

SNA can be used to investigate the fabric of interpersonal relationships with the nodes representing individuals and the links between the nodes representing the relationships between the individuals, such as information exchange [24]. Information exchange can be mapped within sociograms where the actors are shown as nodes and information exchange are shown as links in the graph [55].

In the ego network, the changes of the stakeholders' positions in the information exchange network can be derived from the analysis of the network nodes. Due to the bidirectional nature of information exchange, the information exchange network is bidirectional. The strength of information exchange can be measured by the frequency of interaction. In addition, the networks can be divided into weighted networks and binary networks. The weighted networks imply that the links are various in strength or frequency, while the binary networks only indicate there is a relationship between the actors [56]. Due to different exchange frequencies among stakeholders, the weighted network is adopted in the Model 3.

5.3. Determination of Network Indices

According to the social network theory suggested by Borgatti et al. [57], network metrics can be calculated to understand the characteristics of the ego-centric clustering in construction projects resulting from the application of BIM technology. Suggested by Wang, Thangasamy, Hou, Tiong, and Zhang [7], the social networks can be investigated from network-level and node-level. To explore the structure of the information exchange networks in direct contact with the focal actor (e.g., BIM manager) and the impact of the focal actor (e.g., BIM manager) on the information exchange networks, the network-level measures (i.e., density, average degree, effective size) and the node-level measures (i.e., degree centrality, betweenness degree, and clustering coefficient) are derived in this paper. Table 1 summarizes the major network measures in Model 3.

Table 1. Selected network properties in Model 3.

Level	Metrics	Definition
Node-level	degree centrality	the number directly linked to the nodes [33]
	betweenness centrality	the frequency of a node falling on the shortest path between any two other non-adjacent nodes in the system [7]
	Clustering coefficient	the average ratio of existing links connecting a node's neighbors to each other to the maximum possible number of such links [7]
Network-level	density	the number of ties in a network divided by the maximum number of ties [18]
	average degree	the average number of ties connected to a node [7]
	effective size	the average non-redundancy score of all the primary alters [58]

5.3.1. Node-Level Metrics

Social structures and interpersonal relationships can be visualized as social networks. Social networks can be constructed by the nodes corresponding to people and links between these nodes (i.e., relationships between those people). Degree centrality is the direct metric to characterize node centrality in network analysis, which measures the degree of closeness that one node connected to another. The higher centrality degree means the actor plays more important role in the network. An individual with a high degree centrality is a good communicator and has frequent direct contact with others in the network. Effective application of BIM technology requires direct contact between the BIM manager and other actors. BIM manager should have high degree centrality [37]. Equation (1) shows how to calculate the degree centrality:

$$Cd(N_i) = \sum_{j=1}^{n} a_{ij}(i \neq j), \tag{1}$$

where:

n is the number of alters,
$Cd(N_i)$ refers to the degree centrality of node i,
a_{ij} refers to the number of direct relationships of node i with node j,
a_{max} refers to the maximum possible value of a_i

In addition, the indicator needs to be standardized to eliminate the impact of network scale on the metric so that the values from different project communication networks are comparable. The standardized degree centrality of the ego can be calculated by Equation (2).

$$Cd_e = \frac{\sum_{j=1}^{n} a_j}{na_{max}}, \tag{2}$$

where:

Cd_e refers to the standardized degree centrality of the ego,
a_j refers to the number of direct relationships of the ego with actor j,
a_{max} refers to the maximum possible value of a_j.

Standardize degree centrality varies from 0 to 1. The value of 0 indicates the ego has no direct relationship with other actors, whereas the value of 1 indicates the ego connects with other actors at the highest level.

The significance of measuring betweenness centrality is to explore the core members of the network that lie on the multiple shortest paths of other members. It represents the potential control and impact of a node in the network. A node with high betweenness centrality has more control over resources and greater ability to influence the other nodes [33]. A node with a high value of betweenness centrality could influence the other nodes through control or misrepresent information [32]. Maskil-Leitan and Reychav [37] suggested that the wide application of BIM technology enables direct contact between

BIM project managers and other participants, while achieving high betweenness centrality. Equation (3) shows how to calculate the betweenness centrality.

$$Cb(i) = \sum \frac{g_{jk}(i)}{g_{jk}}, \tag{3}$$

where:

Cb_i is the between centrality of node i,
$g_{jk}(i)$ is number of shortest paths from node j to node k that pass through i,
g_{jk} is number of shortest paths from node j to node k.

The betweenness centrality obtained in this way is affected by the size of the network, which can be eliminated by dividing by C_n^2. Standardized betweenness centrality of the ego can be calculated by Equation (4).

$$Cb_e = \sum \frac{g_{jk}(e)}{C_n^2 g_{jk}}, \tag{4}$$

where:

Cb_e refers to the standardized betweenness centrality of the ego,
C_n^2 refers to the number of permutations of n alters taken 2 at a time,
$g_{jk}(e)$ is number of shortest paths from node j to node k that pass through the ego.

Clustering coefficient (also called cluster coefficient or clustering coefficient) is a coefficient used to describe the degree of clustering between vertices in a graph. Specifically, clustering coefficient can be understood as the degree of inter-connection between the neighbors of a node. Du, Zhao, Issa, and Singh [34] suggested that one of the most significant features of BbCNs is the higher clustering coefficients and simultaneously lower path length. Equation (5) shows how to calculate the clustering coefficient.

$$C_e = \frac{2e}{n(n-1)}, \tag{5}$$

where:

e refers to the number of connections between alters,
C_e refers to the clustering coefficient of the ego.

5.3.2. Network-Level Metrics

Network-level analysis aims to analyze and measure the characteristics of the whole network, in order to enhance the understanding of information exchange from the perspective of an entire organization. Measures of interest at the network level are density, average degree, and effective size.

Network density measures the closeness of ties among actors [37]. Generally speaking, network density determines the effectiveness of communication and information exchange between participants, that is, the higher the network density, the more effective communication and information exchange [25]. However, since studies of information exchange generally use undirected networks, low network density instead indicates effective information exchange. Therefore, low network density indicates that the application of BIM technology has a positive effect on promoting collaboration.

The ego-centric network is used to analyze the network structure of the focal actor's perceptions, and the focal actor is asked to report the relationships between the other actors he/she perceives. Thus, the density of Model 3 measures the frequency of communication and information exchange among project actors as perceived by the focal actor.

In Model 3, the focal actor is asked to report the relationships between other actors that he/she perceives, and the network constructed in this way can be analyzed through an egocentric network. Thus, the density of Model 3 measures the frequency of communication and information exchange between the project actors as perceived by the focal actor. The ego-centric network is multi-valued and undirected, so the calculations of the network density in Model 3 are given below, respectively.

$$D_e = \frac{\sum a_j}{C_n^2 a_{max}}, \tag{6}$$

where:

D_e refers to the density of ego-centric network,
a_j refers to the link strength between ego and node j.

The average degree measures the average number of ties connected to a node [7]. According to Costa et al. [59], the average degree can be used to measure the global connectivity of a network. Equation (7) shows how to calculate the average degree:

$$\overline{Cd} = \frac{1}{n}\sum_{i=1}^{n} Cd_i, \tag{7}$$

where:

$\overline{Cd}$ refers to the average degree of ego-centric network,
Cd_i refers to the standardized degree centrality of actor i.

The effective size is the number of non-redundant alters to which the ego is connected, which indicates the control of the ego over the alters. It is given by the number of alters in the ego network minus the average degree of the alters in the ego network without considering the edges adjacent to the ego [60]. For example, three people are not connected to each other, so the effective size of the network is three. Alternatively, A is connected to all of three people, and the three people are connected to each other. In this case, the size of A's network seems to be three, but these connections are 'redundant' because A can get information about the remaining two people by contacting one of the three people. Therefore, the effective size of the network is one. Equation (8) shows how to calculate the effective size of Model 3.

$$ES_e = n - \frac{2t}{n}, \tag{8}$$

where:

ES_e refers to the effective size of the ego network,
n refers to the number of alters,
t refers to the total number of ties to the ego network while excluding the ties to ego.

5.4. Example Case Study

5.4.1. Project Background

Two projects of similar size, one with BIM and the other without, were carefully selected by considering their comparability. Both projects were sizable public housing blocks located in China, and they adopted the same design style; thus, their construction processes are largely comparable. The main application of BIM in the project includes: (1) pipeline collision check and space optimization; (2) construction progress simulation; (3) progress tracking; (4) virtual construction simulation.

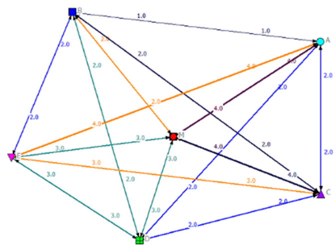
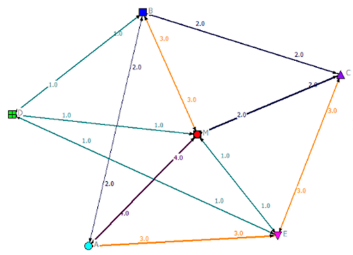
5.4.2. Data Collection

Base on the network metrics derived in above section, it is possible to compare different ego-centered networks. According to the research assumptions, the interaction data between the alters is collected through the perception of the self. An in-depth interview is necessary to test the model assumptions. The quality of data collection relies heavily on how to guide respondents to provide accurate descriptions of their surrounding networks, which places greater demands on research design [61]. As suggested by McCarty, Lubbers, Vacca, and Molina [48], a face-to-face interview can be the most appropriate method to collect data for the personal network. Six experts attended to the interview, all of whom worked for the above two projects. Their specializations rang from the owner, designer, general contractor, and supervising engineers, which can really reflect the project collaborative relationship and avoid conflicting feedbacks in interview. An ego network analysis was conducted to compare the differences between the BIM and non-BIM projects.

5.4.3. Model Validation

The metrics derived in above section were used to examine the usefulness of Model 3. It is vital to assess the usefulness of the proposed model after evaluating the primary model assumptions [62]. As indicated in Table 2, four indices (Degree centrality, Clustering coefficient, Density, Effective size) were used to analyze the efficacy of Model 3 quantitatively. The ego network analysis shows a favorable trend of more effective communication networks for BIM projects. It echoes the previous findings by Du, Zhao, Issa, and Singh [34]. A variety of network property changes caused by implementing BIM signify improved communications with ease and efficiency of transferring information in the project communication network.

Table 2. The major network indices for the ego network.

	BIM Project	**Non-BIM Project**
graphical presentation		
Degree centrality	0.8	0.55
Clustering coefficient	1	0.6
Density	0.65	0.38
Effective size	1	2.6

As shown in Table 2, BIM projects tended to have a greater number of direct connections among the nodes, providing more effective channels for information exchange. As shown in Table 2, a higher density can be seen in a more connected network. From a project management perspective, a more connected communication network enables more effective channels for information exchange and interpersonal communication throughout the network. The ease of spreading information within the network is a helpful condition for coordination between the individuals to complete a task. The higher clustering coefficient values observed in BIM projects mean that more nodes have direct connections with each other than in non-BIM projects.

6. Discussions

This paper not only proposes that network research for construction projects needs to be conducted in multiple dimensions, but also develops an integrated framework with three network models that can be used for multi-level network analysis. It was discovered that the application of BIM disrupts the interaction between individuals and industry organizations from time and spatial dimensions. However, the majority of recent attention has been focused on specific projects, or the collaborative networks among multiple organizations [9]. Additionally, there is a lack of research on the individual-centric clustering. It is worth noting that the majority of recent attention about the project communication networks has been focused on industry and project levels. The network analysis at the individual level is under-researched, so we actively explore how to extend the scope of the network analysis from the project and industry level to the individual level.

Information exchange in construction projects often involves a large number of participants and subsequent interconnections. These interconnections are multilayered, including multiple relationships, conceptualized as a relationship network [33]. Network range, network level and research design were proposed as the three dimensions in network research for construction projects. Zhang and Ashur [15] analyzed the structural properties of project networks at three network levels: macro-level (the whole network), meso-level (the subset of nodes), and micro-level (the nodes and links). However, most of the SNA in CPM research is at the macro-level, while the network structure at the meso and micro level has not been systematically investigated [16].

SNA has been widely used for project communication networks over the past two decades [24], mostly being used to analyze static networks by taking a snapshot of the social interactions at a particular point in time [25] or aggregated networks over a period of time [26]. This approach assumes some level of stability in a project communication network over time [2] and calls for more longitudinal studies that examine project networks at multiple points of time in its evolution [21]. According to the theoretical analysis, Models 1, 2, and 3 are applicable for static or longitudinal analysis. However, the lack of data and ingenious research design makes the potential of network models to investigate information exchange of construction projects far from being exhausted. Model 1 can be used to analyze the industry-level network, particularly the inter-firm networks. Model 2 can be used to analyze the project-level networks, which characterize interpersonal or inter-organizational relationships within an individual construction project [45]. The application of BIM has given rise to ego-centric clustering in project networks. Previous studies have mentioned the BIM-centered clustering, e.g., Maskil-Leitan and Reychav [37] discussed the concepts of ego-network cluster in CPM research. To explore the ego-centric clustering, Model 3 was constructed in this study. A case study was used to illustrate the usefulness of Model 3, in which two projects were used to compare the differences between the BIM and non-BIM projects. The core idea is to find basic community of direct contacts with the individual and to cluster its members. The size measure is used as a community detection algorithm to indicate the number of participants in the clustering. This principle can also be applied to agents of the BIM manager, such as the coordinator. Therefore, on the basis of the accepted terminology in SNA, whereby the size of the ego network is the number of nodes that are close to the ego in addition to the ego itself, it is possible to calculate the direct connections of the BIM manager. The findings provide evidence to previous theoretical arguments, e.g., BIM can foster multidisciplinary collaboration [40], make communication easier and more effective [34], and change the organizational structure [21].

7. Conclusions

There has been increasing interest in analyzing the complex and dynamically changing project communication networks. A general theoretical framework is proposed to associate the multiple dimensions in network research with the network models at the industry, project, and individual levels. This outline can provide building blocks for analyzing project communication networks and highlight the methodological potential of SNA. This is a significant gap in the existing knowledge and represents the first time that such a framework has been proposed. The two SNA application approaches whole network analysis to reveal the network structure and explore the impact of the structure on the actors within it [17–19] and ego network analysis to gain a more comprehensive understanding of the individual's behaviors in the network [31,32]—as well as provide a new model to explore the project communication networks at the individual level. The lack of data and an ingenious research design hinder the application of the network models. These insights can lead to a new exploitation of research design, network models, and data collection of network analysis.

The application of BIM has triggered individual-centric clustering, but the ego network model is currently used in the fields of sociology and psychology. Some scholars proposed to use the ego network model to explore the BIM-centered clustering (e.g., Maskil-Leitan and Reychav [37]); however, the theoretical model and empirical evidence are still lacking. A case study was used to illustrate the usefulness of Model 3. The results show that BIM projects tended to have a greater number of direct connections among the nodes, providing more effective channels for information exchange. The ego-centric model offers a significant contribution to the information exchange analysis which may open up new research opportunities in the CPM literature. There are many potential application scenarios to be further analyzed in the future, e.g., it is possible to compare different ego-centered networks.

The proposed model contributes to exploitation of a new network model and developing an integrated framework for multilayered network analysis in CPM, which is heuristic to scholars who are interested in project communication networks. This framework contributes to extending the scope of the network analysis from the project (e.g., Du, Zhao, Issa, and Singh [34]) and industry level (e.g., Cao, Li, Wang, Luo, Yang, and Tan [8]) to the individual level. Additionally, the proposed model gives the scientific capability for the decision-maker to better evaluate what benefits can be gained through the application of BIM technology and make a decision by quantifying the impact of BIM technology on construction projects. As such, the study can serve as a first step in bridging the theory-implementation gap and help decision makers better understand the role and potential contribution of BIM managers.

Limitations of the research are acknowledged as follows. First, the basic concepts and limitations of Models 1 and 2 were discussed in this paper, and more research will be conducted to evaluate the appropriateness of Models 1 and 2 in the future. Second, this research is primarily concerned with the development of an integrated framework for theorizing about the network models in CPM research, so a simple case study was used to illustrate the usefulness of the Model 3. Further research should collect more data and add more case studies to support the results. Another limitation is that the case study focuses on one application scenario. So future research should investigate the different application scenarios of Model 3. Lastly, this study focused on the review and theoretical analysis of the two commonly used network models of SNA, i.e., the whole network model and ego network model. More network models should be discussed in the future.

Author Contributions: Conceptualization, Y.Y. and X.L.; methodology, Y.Y.; software, X.L.; validation, Y.Y. and X.L.; formal analysis, X.L.; writing—original draft preparation, X.L.; writing—review and editing, Y.Y.; supervision, Z.Z.; project administration, Z.Z.; funding acquisition, H.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (71673240, 42271179 and 71772163), the Fundamental Research Funds for the Central Universities, Guangzhou Social Science Planning Project (2020GZYB94), and funded by Center for Balance Architecture, Zhejiang University.

Data Availability Statement: The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Building information modeling	BIM
BIM-based construction networks	BbCNs
Construction projects management	CPM
Social network analysis	SNA

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