Research Article

Comparing Project-Based Collaborative Networks for BIM Implementation in Public and Private Sectors: A Longitudinal Study in Hong Kong

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Due to the great potential of building information modelling (BIM) to address traditional design and construction problems, the governments in many regions, such as Hong Kong, have released related policies to advocate the use of BIM in public projects in recent years. Therefore, BIM might advance differently in the public and private sectors in these regions. Using the social network perspective and a longitudinal data set on BIM-based construction projects in Hong Kong from 2002 to 2017, this study quantitatively characterizes how the structural characteristics of the project-based collaboration networks for BIM implementation in the public (PUCN) and private sectors (PRCN) evolve differently over time. The empirical results provide evidence that both PUCN and PRCN have become increasingly dense and developed around some "centered" nodes during the examined period. However, it is revealed that PUCN exhibits a more significant trend in network closeness and centralization. Through characterizing the "centered" nodes individually, the results also reveal that local owner organizations generally play more active roles in PUCN, while local design and construction organizations generally play more actively in PRCN. The results also provide evidence that the evolution of the two networks closely relate to each other, with the design and construction organizations involved in PUCN during early periods significantly influencing the evolution of PRCN in the later periods. The findings not only provide a dynamic network view of how industry organizations interact with each other in BIM implementation practices across different types of projects but also provide insights into how relationship networks can be managed to facilitate the diffusion of innovations in the construction industry.

1. Introduction

The construction industry worldwide has long been criticized for its slowness to adopt innovative technologies and processes to address the performance problems of cost overruns, schedule delays, and quality inferiorities [1–4]. As an innovative technology to parametrically model and integrate the design, construction, and operation information throughout the project lifecycle [5], building information modelling (BIM) has widely been recognized to be capable of solving the performance problems rooted in traditional design and construction processes [6]. Like many other innovative technologies in the construction domain, BIM is a systemic innovation, with its successful implementation in

a construction project, generally requiring the close collaboration of multiple organizations [5, 7]. In order to facilitate the adoption of BIM and maximize its potential benefits across the industry, governments or their affiliated organizations in several regions, such as Denmark, Hong Kong, Singapore, South Korea, the UK, and the USA, have released related policies or plans to advocate the use of BIM in the industry, especially in public projects [8–11].

Due to the great potential of BIM to address the performance problems rooted in traditional design and construction processes, the past decade has witnessed increasing efforts to theoretically or empirically investigating BIM-related issues [12]. To date, much of the empirical investigations on BIM has focused principally on identifying

the factors influencing BIM adoption or the performance outcomes of BIM implementation at the project level [13–15]. Considering the project-based nature of the construction industry and the systemic-innovation nature of BIM, recent years have also witnessed scholarly efforts of aggregating project-specific collaborative relationships related to BIM implementation in different project contexts as industry-level collaborative networks [16]. They aim to characterize how the knowledge related to BIM implementation diffuses among organizations in the industry. To date, however, related research in this stream is still at an infant stage. In recent years, the governments or their affiliated organizations in many regions, such as Hong Kong, have released related policies to mandate the use of BIM in public projects. As such, BIM might advance differently in the public and private sectors in these regions. However, scant scholarly attention has been devoted to investigating the project-based collaborative networks for BIM implementation from a comparative perspective. What is the difference between the structural evolution of PUCN and PRCN? Is the evolution of the collaborative network in the private sector influenced by the network in the private sector? Answering these questions through a comparative study could reveal how BIM technology diffuses differently in different sectors under the influence of institutional pressures. It could also provide insights into how government policies facilitate the advancement of innovations in the project-based construction industry.

Using the social network perspective and longitudinal data on BIM-based construction projects in Hong Kong during 2002–2017, this study aims to quantitatively compare the structural evolutions of PUCN and PRCN. Furthermore, the sturdy also aims to investigate how these two networks relate to each other during the evolution process. The relationships among the three following types of organizations are specifically investigated in this study due to their critical roles played in project-level BIM implementation processes [7, 17]: owners, design consultants, and main contractors. The remainder of this paper will illustrate the background of the collaborative relationship in the construction industry from the network perspective and then use the longitudinal data to conduct the network analysis. It will then compare the network analysis results and analyze the associations between different networks. Finally, the descriptive and comparative analysis results are discussed and conclusions drawn.

2. Materials and Methods

2.1. Network Perspective on Collaborative Relationships in the Construction Industry.
As a theoretical lens that has been used in a wide variety of social life areas, the network perspective focuses not only on an individual's social attributes but also on broader relational structure characteristics to explain organizational issues [18]. This perspective has also attracted increasing the academic interest to explain the organizational issues in the construction domain during the past two decades [19]. The fundamental logic under this theoretical perspective is that the structure of relationship

ties within which an actor is embedded has a significant influence on the behaviors and performance of the actor [18, 20]. The empirical research in the construction field under the network perspective covers a wide range of relationship types. Examples of these relationships within individual projects include interpersonal communication relationships related to project safety and success [21, 22], interorganizational contractual coalition relationships [23–25], interorganizational trade relationships based on spatial physical proximity [26], and interorganizational information exchange relationships related to organizational efficiency and team performance [22, 24, 27]. Under the network perspective, the construction organizations will continuously interlink with each other as the new construction projects start. As such, the interfirm relationship ties will gradually evolve into more complex collaborative networks. Recently, increasing investigations have also been conducted to identify project-based macronetworks and characterize how different organizations interact with each other across projects at the industry level. The topics examined in these investigations include the structural attributes of the static collaborative networks for overseas construction projects [28, 29], the impact of project-based collaborative networks on organizational competitiveness and strategy [30], the structural attributes of the innovation collaborative networks in prize-winning projects [31, 32], and the micromechanisms underpinning the evolution of project-based collaborative networks [16, 33]. Regarding the project-based collaborative networks for the implementation of innovative technologies, recent years have also witnessed increasing attempts to investigate the collaborative networks for BIM implementation within specific projects [34, 35, 36]. More specifically, Cao et al. [16, 37] investigated the collaborative networks of BIM implementation in the Shanghai construction industry, not only elucidating the microfoundations in network dynamics but also identifying the relationship between network structure and organizational competitiveness. Based on the extant research and taking into account the underlying differences of BIM implementation between different sectors, this study further compares PUCN and PRCN from a dynamic network perspective.

2.2. Network Data Collection and Classification.
A longitudinal data set of BIM-based construction projects conducted in Hong Kong from 2002 to 2017 was used to empirically explore the characteristics of collaborative networks for BIM implementation. As one of the economic centers in Asia, Hong Kong is one of the pioneering regions globally to officially advocate and facilitate the development of BIM in the construction industry. The deployment of BIM in Hong Kong could date back to more than a decade ago and was pioneered by some public client organizations such as the Housing Authority. However, the advancement of BIM in the regional construction industry is still not widespread when compared with the leading practices worldwide [38]. While the construction industry in Hong Kong is relatively small compared with other regional construction industries,

only a limited number of large-scaled owners, design consultants, and main contractors have been involved in BIM implementation practices. As such, it would be appropriate to use the snowballing data collection method based on these large and prominent organizations to identify other linked organizations through project-based collaborative relationships for BIM practices, as well as BIM-based projects of other organizations. During the data collection period, based on the correspondence information obtained from the Hong Kong Institute of Building Information Modelling (HKIBIM), organizations winning the Autodesk Hong Kong BIM Awards during the past decade were first contacted through telephones or onsite visits. Semistructured interviews were then conducted with BIM directors or other informed professional individuals in these organizations to get the lists of their BIM-based construction projects, the names of other organizations involved in BIM implementation in these projects, and the details of BIM implementation practices in these projects.

Further information on these projects (i.e., project size, project type, project starting year, and project participant organizations) and involved organizations (i.e., locations of headquarters) were obtained from the BCI Asia database and firm websites. Other related organizations were then further contacted based on the snowballing process until no new BIM-based construction project can be further identified. After snowballing data collection and the omission of 15 project cases with incomplete or wrong information, a total of 192 BIM-based projects that started during 2002–2017 and 212 related organizations including owners, design consultants, and main contractors were eventually included in the analysis. As this study mainly focuses on characterizing the differences of BIM practices between the public and private sectors, the data set was further classified into two categories: the public BIM-based projects and the private BIM-based projects. There is a total of 100 public projects with 101 related participant organizations (including 16 owners, 40 design consultants, and 45 main contractors) and a total of 92 private projects with 122 participant organizations (including 51 owners, 43 designers, and 28 general contractors). Demographic information of the two data sets and related owners, design consultants, and main contractors involved in the BIM implementation practices of these projects is illustrated in Table 1. It is illustrated that the BIM-based projects in public and private sectors are both diverse in terms of project type and project participant organizations.

Based on the two categorized data sets, two corresponding project-based collaborative networks were mapped and analyzed in this study: the collaborative network for BIM implementation in the public sector (i.e., PUCN) and the collaborative network for BIM implementation in the private sector (i.e., PRCN). As the two collaborative networks examined in this study depict the relationships among owners, design consultants, and main contractors, one-mode matrices (i.e., actor-actor matrices) were used to represent the relational data among the involved organizations. In one-mode networks, nodes only include actors (i.e., owners, design consultants, and main

contractors). The corresponding matrices for the investigated networks are composed of i rows and j columns with both i and j representing the number of examined organizations in the specific network. The number in each cell r_{ij} in these matrices represents whether the two corresponding organizations (i.e., i in the row and j in the column) are directly linked or not in the examined BIM-based projects in the one-mode network matrix. If the two organizations have jointly implemented BIM in the same project once and thus formed project-based collaborative ties for BIM implementation, the corresponding cell is denoted as 1 and denoted as 0 otherwise. Considering the reciprocal nature of the collaborative relationships for BIM implementation in construction projects, these network matrices for different time windows in this study are all symmetrized.

2.3. Network Measures. Descriptive analysis of the examined networks characterizes both the macrostructures of the networks and the individual performance of network nodes. The indicators used to describe the macrostructures of the networks are as follows:

(1) Linked node fraction, which refers to the ratio of the number of linked nodes to the whole nodes in a network.

(2) Average node degree, which refers to the average number of ties that each node has.

(3) Network density, which refers to the proportion of all possible dyadic connections that are actually present and calculated as the sum of the ties divided by the number of possible ties (i.e., the ratio of all tie strength that is actually present to the number of possible ties).

(4) Main component fraction, which refers to the proportion of the main component emerged in the network. The main component (or the giant component) refers to the node group with the largest number of interconnected nodes.

(5) Average distance among main component nodes, which refers to the average of the geodesic distances between the nodes in the main component.

(6) Clustering coefficient, which measures the degree to which nodes in a graph tend to cluster together. The global clustering coefficient is calculated as the number of three times of triangles over the total number of triplets. In this study, the weighted clustering coefficient, which refers to the weighted mean of the clustering coefficient of all the actors each one weighted by its degree, is specifically used. According to Watts and Strogatz [39], the clustering coefficient and the average distance together can reflect whether a network exhibits small-world properties.

(7) Graph centralization, which measures the degree to which the centrality of the most central node exceeds the centrality of all other nodes in an overall network

TABLE 1: Demographic information of projects and organizations under study.

Variable	Category	Number	Percentage (%)
Project nature	Public	100	52
	Private	92	48
Project starting year in public projects	Before 2009	11	11
	2010-2011	14	14
	2012-2013	24	24
	2014-2015	22	22
	2016-2017	29	29
Project starting year in private projects	Before 2009	15	16
	2010-2011	12	13
	2012-2013	16	17
	2014-2015	27	29
	2016-2017	22	24
Role of participant organizations in public projects	Owners	16	16
	Design consultants	40	40
	Main contractors	45	45
Role of participant organizations in private projects	Owners	51	42
	Design consultants	43	35
	Main contractors	28	23

[40]. In this study, it is calculated as a ratio of the degree centrality excess to the maximum value possible (i.e., the degree centrality in a perfect star network of the same size). Its values vary between 0 to 1, and 1 represents that there is one point which dominates the entire network with regard to degree centralization.

(8) Core-periphery structure, which divides network nodes into two classes (one is the core, and one is the periphery) and identifying the densest core but sparsest periphery in an overall network. In this study, the core-periphery analysis is conducted to further investigate the tendency of the network developing around certain nodes based on the results of other network indicators.

(9) Power-law distribution, which investigates the cumulative probability of nodes whose degree is larger than or equal to K (represented as $P(K)$), to assess the uneven distribution of the network ties quantitatively. The power-law analysis in this study is conducted based on the results of other network indicators.

With regard to the performance of individual nodes in each collaborative network, indicators of degree centrality and eigenvector centrality were selected to reflect the quantity and quality of the connections of involved organizations [20]. Degree centrality, which is a primary measure of the network at the nodal level, refers to the number of ties that a node has [40]. In a project-based collaborative network, a relatively high degree centrality indicates that the corresponding organization has more connections of cooperation with other organizations and is thus more prominent in the entire network. While the degree centrality identifies influential nodes by counting the number of ties each node has, eigenvector centrality identifies another kind of essential nodes. It weighs a node's degree with an eigenvector coefficient, which is based on the idea that a node

connected to other influential nodes that are well-connected themselves is also more central and influential in the entire network [41]. The analysis process of this study is depicted in Figure 1.

3. Results and Discussion

In order to conduct the comparative analysis of the networks of PUCN and PRCN, the descriptive analysis in each sub-network was first calculated with *UCINET 6.647* and then visualized through its embedded drawing package *NetDraw*. This study aggregated the data on collaborative relationships before different observed time points to construct project-based collaborative networks. While the number of BIM-based projects before the year 2009 is too small to conduct a social network analysis, the two collaborative networks were both investigated starting from the year of 2009. And the five investigated times were 2009, 2011, 2013, 2015, and 2017, with each network covering the collaborative ties in the BIM-based projects started before and in the specific year. The calculation of the social network indicators was based on binary networks, in which the undirected ties among owners, design consultants, and main contractors were dichotomized as 1 or 0.

3.1. Results of the Descriptive Analysis of the Network Characteristics of PUCN. Based on the relational matrices describing the undirected collaborative ties among owners, design consultants, and general contractors in PUCN, the collaborative networks up to the five observed years (namely, 2009, 2011, 2013, 2015, and 2017) are visualized in Figure 2. It plots the macrostructures of PUCN based on the aggregated ties up to the specific years and helps to initiatively understand how the network evolves over time. In Figure 2, different node shapes in the networks are used to distinguish the different roles of project participant organizations, with circles indicating owners, squares indicating design
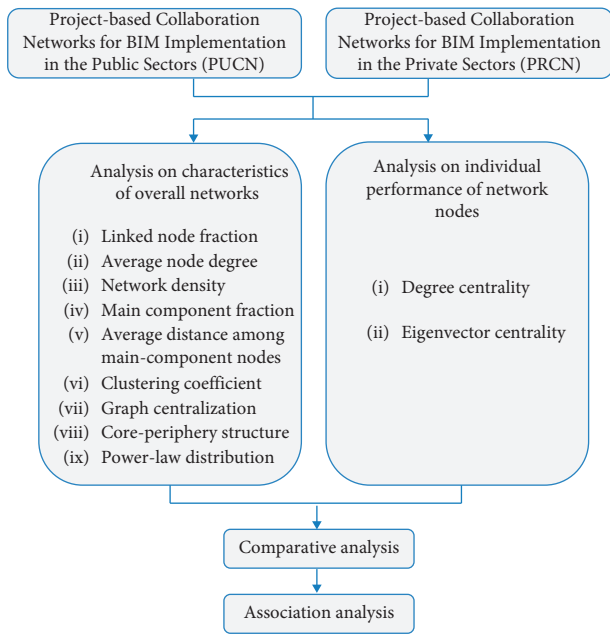
FIGURE 1: Research analysis process in the study.

consultants, and diamonds indicating main contractors; different node colors are used to distinguish the organization nature, with the color of dark blue representing local organizations and the color of light blue representing overseas organizations; and different node sizes represent different degrees of the nodes in the network (i.e., the number of ties linked to the node in the network).

As shown visually in Figure 2, the structure of PUCN expands greatly during the examined period and there is a distinct tendency for the network to become denser over time. The seven examined network structure statistics were then calculated for the different time windows to quantitatively characterize the structural evolution of PUCN. It is evident in Table 2 that the linked node fraction has shown a rapid growth during the observed time period, and the value in 2017 (100%) is almost ten times than that in 2009 (10.89%). This reveals that BIM-based cooperation among the participant organizations has developed very fast in construction projects in the public sector, and an increased number of industry firms have been involved in these projects. The values of the average node degree and network density have also increased substantially and reached 7.05 and 0.07 in 2017, respectively. Both of the statistics have increased by nearly tenfold during the last 16 years.

The structure topology mapped in Figure 2 also reveals that the examined network has developed cohesively over time. All the linked nodes within PUCN have converged as a unique giant component (i.e., the largest component) at the start of 2011. This explains the equivalence of main component fraction to the linked node fraction during 2011 to 2017 in Table 2. The sustained emergence of the unique giant component indicates that the newly participant organizations in the collaborative network have always had a very close relationship with the previous participant organizations through direct or indirect links. As such, they could join in the largest collaborative hub (the largest component)

very soon during the period under study. While the main component fraction has increased significantly from 10.89% in 2011 to 100% in 2017, the average distance among the main component nodes (i.e., the unique main component in the network) has not changed significantly but stayed around 2.61 at the same level. It suggests that any two reachable organizations in the largest component can reach each other within 3 steps or less. These values of network distance among the main component nodes are relatively similar to that of random networks of the same size (the average distance values of the random graphs whose size is equivalent to the main component in 2009, 2011, 2013, 2015, and 2017 are 2.40, 2.30, 2.32, 2.31, and 2.36, respectively). Furthermore, the values of the clustering coefficient in the examined period have continuously decreased, and the diminishing rate slowed down after 2013. These values are much larger than those of random networks with the same number of linked nodes (the values for random graphs of its size for 2009, 2011, 2013, 2015, and 2017 are 0.25, 0.12, 0.09, 0.09, and 0.07, respectively). Taken together the relatively short distance and high clustering coefficient together suggests that the structures of PUCN exhibit small-world properties [39].

Despite the obvious increase of both component size and density in the examined network, the value of the network centralization, increased from 0.05 in 2009 to 0.23 in 2017. These relatively small values indicate that there is a slight tendency for the network to develop around certain prominent organizations over time, which can also be intuitively observed from the visualized network structures shown in Figure 2. To investigate this tendency further, the core-periphery analysis was conducted to explore the network structure properties in each examined time window. As illustrated in Table 3, the analysis results reveal that PUCN has displayed the core-periphery structure during the examined period with final fit values being around 0.5. It indicates that the examined network structures approximate a pure core-periphery structure at a relatively high level. The results also reveal that less than 25% of the network nodes in PUCN are interconnected closely and thus positioned in the core. And a majority of the network nodes are loosely connected and located in the periphery parts. This study further conducted the degree power-law analysis. Figure 3 plots the result of the cumulative degree distribution at the time of 2017 in the double logarithmic coordinate system, which shows that the cumulative degree distribution $P(K)$ decays as a power-law scaling $P(K) \sim 7.352 \times K^{-1.585}$. This result suggests the scale-free characteristic [42] of PUCN. The result indicates that there is a small proportion of centrally positioned that have a large number of ties (have a high degree), while there is a large majority of peripherally positioned that have only a few ties (have a low degree). Taken together, these results provide clear evidence for the uneven distribution of project-based collaborative ties for BIM implementation among industry organizations during the investigated period.

To further characterize the uneven distribution of project-based collaborative ties in PUCN, degree centrality and eigenvector centrality were then calculated to identify
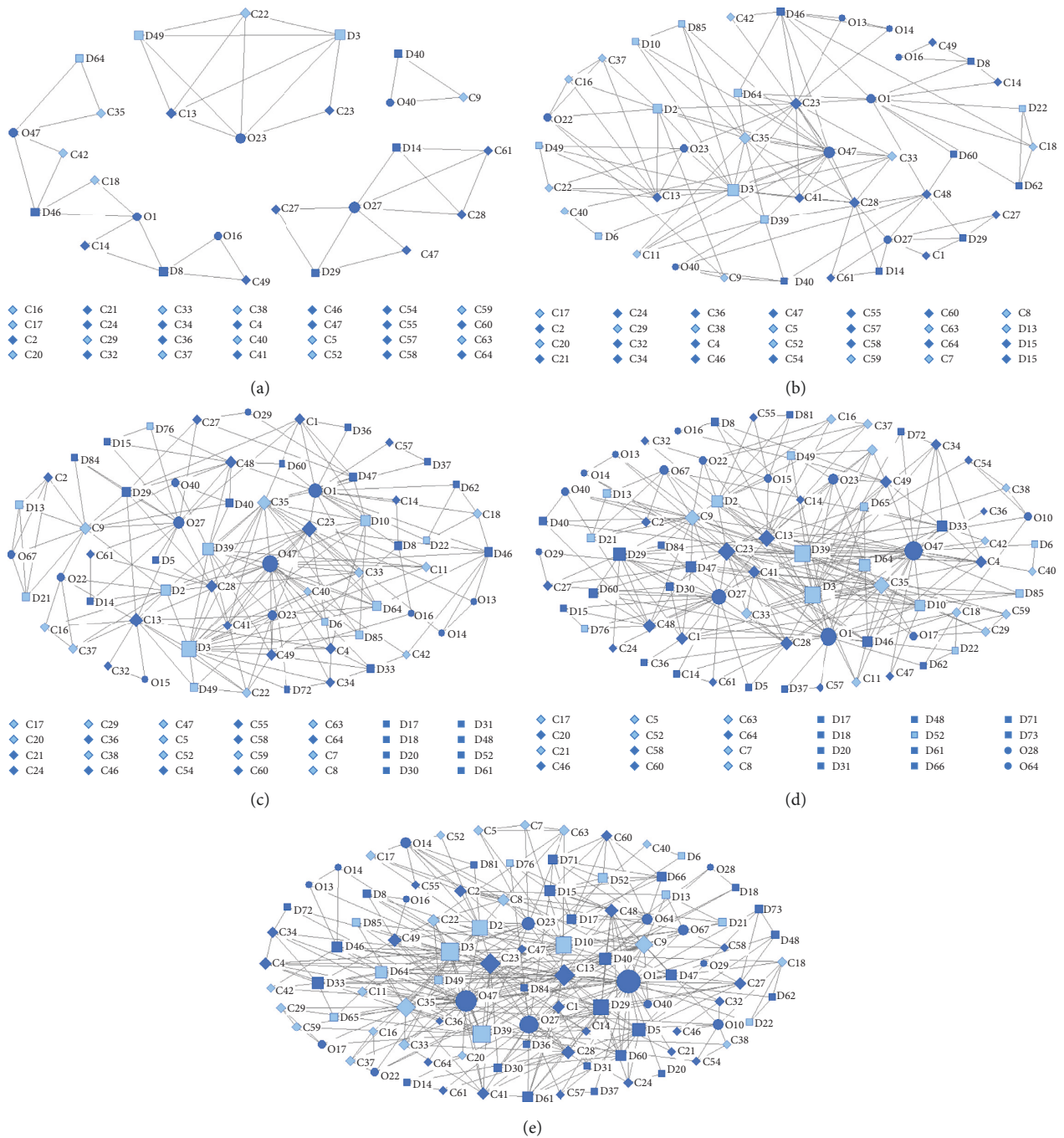
Figure 2: Evolution of network structures of PUCN in (a) 2009, (b) 2011, (c) 2013, (d) 2015, and (e) 2017.

Table 2: Changes in network structure statistics for PUCN.

Indicators	2009	2011	2013	2015	2017
Linked node fraction (%)	26.37	44.55	63.37	76.24	100.00
Average node degree	0.81	2.34	3.80	4.99	7.05
Network density	0.01	0.02	0.04	0.05	0.07
Main component fraction (%)	10.89	44.55	63.37	76.24	100.00
Average distance among main component nodes	2.50	2.72	2.68	2.52	2.64
Clustering coefficient	0.68	0.46	0.37	0.33	0.32
Graph centralization	0.05	0.14	0.19	0.20	0.23

TABLE 3: Core-periphery structure in PUCN.

Time points	Density of linkages		Number of nodes in the core	Final fitness
	Core	Periphery		
2009				
Core	1.000	0.004	5	0.505
Periphery	0.004	0.006		
2011				
Core	0.893	0.048	8	0.517
Periphery	0.048	0.013		
2013				
Core	0.449	0.055	17	0.474
Periphery	0.055	0.015		
2015				
Core	0.462	0.079	19	0.511
Periphery	0.079	0.015		
2017				
Core	0.402	0.087	24	0.437
Periphery	0.087	0.029		
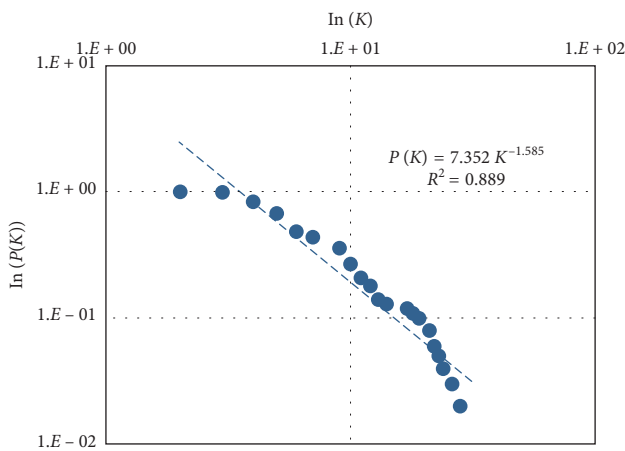
FIGURE 3: Power-law distribution of node degrees in PUCN in 2017.

$P(K) = 7.352\,K^{-1.585}$
$R^2 = 0.889$

TABLE 4: Five-top ranked organizations in PUCN during 2002 to 2017.

Measure	2009	2011	2013	2015	2017
Degree centrality	O27	O47	O47	O47	O1
	O23	D3*	D3*	O1	O47
	D3*	C23	O1	D39*	C13
	O1	C35*	C23	D3*	O27
	O47	O1	C35*	C23	C23
Eigenvector centrality	O23	O47	D3*	O47	C23
	D3*	D3*	O47	D3*	O47
	D39*	C35*	C23	C23	D3*
	C13	C23	C35*	C35*	C13
	C22*	C28	D39*	D39*	C35*

The capital letter in the code of the organizations represents the organization type (O refers to owners, D refers to design consultants, and C refers to main contractors), and the second digit represents the serial coding number for each organization type. The asterisked organizations are overseas organizations, whereas the nonasterisked are local organizations. For example, D3* refers to the design consultant which is coded as No. 3 among all the design consultants and it is an overseas company/organization, while O27 refers to the owner which is coded as No. 27 among all the owners and it is a local company/organization.

those prominent organizations in the network. Table 4 lists the codes of the organizations ranked top five in terms of both the centrality indicators in the five times. With regard to the measurement of degree centrality, the local owner organizations, the overseas design organizations, and the local construction organizations occupy the top five ranked positions in PUCN. It suggests that these types of organizations have participated actively in public projects and thus established a large number of relationships with other organizations. The local owner organizations accounted for over half of the top-five organizations at the start of 2009, and some of them persistently held the prominent positions in later years (e.g., O1 and O47). Those owner organizations have played a consistent leading role in PUCN. Although some local construction organizations (e.g., C23 and C13) and overseas design organizations (e.g., D3 and D39) have also emerged in the top five ranks since the start, their position rankings are fluctuating and relatively lower than those of owner organizations. With regard to the eigenvector centrality, some overseas design consultants (e.g., D3 and D39) and local main contractors (e.g., C12 and C23) occupy

the top-five ranks. It suggests that these organizations have collaborative relationships with the relatively important or centrally positioned organizations. As such, they can access resources more directly and gain high value of the degree centrality.

3.2. Results of the Descriptive Analysis of the Network Characteristics of PRCN.

With regard to the network of PRCN, this study has also observed the network structure properties at the time points of 2009, 2011, 2013, 2015, and 2017. The structures of the network in different periods are visualized in Figure 4. The representations of node properties in Figure 4 are consistent with that in Figure 2. It is plotted in Figure 4 that the network structures become more cohesive over time and expand around some prominent organizations. Table 5 provides the analysis results of network structure statistics of PRCN over time. It is shown in Table 5
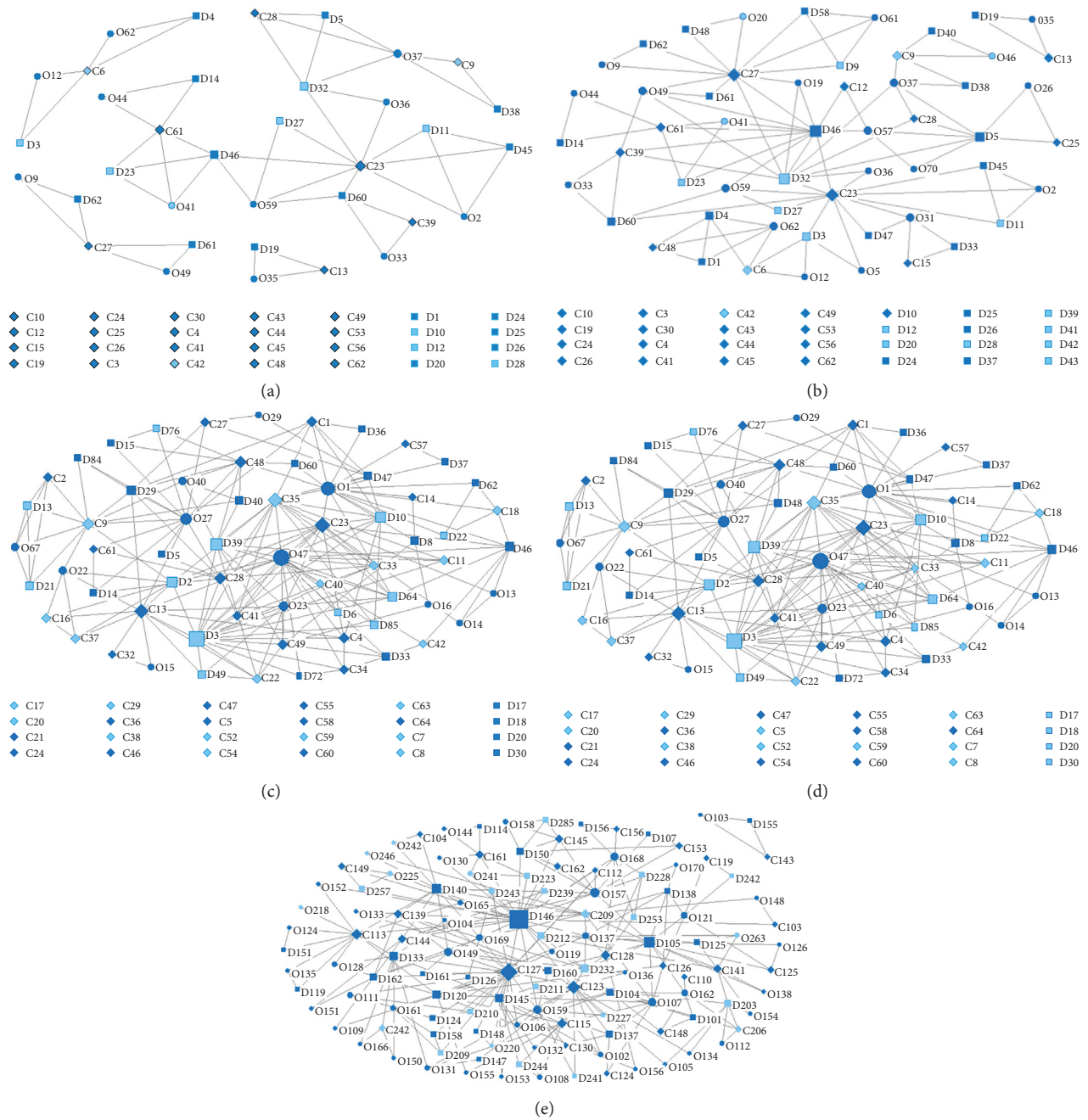
Figure 4: Evolution of network structures for PRCN in (a) 2009, (b) 2011, (c) 2013, (d) 2015, and (e) 2017.

Table 5: Changes in network structure statistics for PRCN.

Indicators	2009	2011	2013	2015	2017
Linked node fraction (%)	28.69	45.08	60.66	89.34	100.00
Average node degree	0.85	1.61	2.41	3.67	4.46
Network density	0.01	0.01	0.02	0.03	0.04
Main component fraction (%)	18.03	42.62	60.66	83.61	97.54
Average distance among main component nodes	2.90	3.40	3.50	3.20	3.10
Clustering coefficient	0.51	0.36	0.28	0.23	0.22
Graph centralization	0.07	0.10	0.14	0.20	0.23

that the linked node fraction grew to 100% in 2017, which is nearly to four times that in 2009 (28.69%). Furthermore, the average node degree and network density also exhibit significant increases during the examined period, with the values reaching 4.46 and 0.04, respectively, in 2017.

As plotted in Figure 4, the unique giant component (the unique largest component) has shown up intermittently in PRCN during the examined periods. The independent triangle-shaped component, which consists of one owner, one design consultant, and one main contractor, emerges occasionally but merges into the largest component very quickly. This indicates that there are some burgeoning organizations trying individually to implement BIM in their construction projects. And these organizations are involved in the collaborative networks as the cooperation among these organizations becomes more frequent over time. Despite the giant component expanding fast as time goes on, the distance between the nodes in the components fluctuates around 3.20. It indicates that any two organizations in the largest component of the PRCN could connect with each other within three or four paths. With regard to the clustering coefficient, the value has decreased steadily from 0.51 in 2009 to 0.22 in 2017. The distance between the nodes in the largest component in each examined time window is quite close to that of the random network whose size is equivalent to the largest component of the PRCN (the distance values of the random networks with the same number of linked nodes in 2009, 2011, 2013, 2015, and 2017 are 3.27, 3.15, 3.12, 3.32, and 3.21, respectively). The values of the clustering coefficient are much higher than those of the random networks with the same number of linked nodes (values of clustering coefficient of the random networks in 2009, 2011, 2013, 2015, and 2017 are 0.09, 0.07, 0.05, 0.04, and 0.04, respectively). The small-world properties are thus also characterized in PRCN during the examined period.

The value of the graph centralization has also substantially increased from 0.07 in 2009 to 0.23 in 2017, suggesting that the structures of PRCN have evolved around some specific nodes between 2009 and 2017. The core-periphery structure analysis was further conducted to identify the densest core and the sparsest periphery in the collaborative networks. The results provided in Table 6 indicate that the structures of PRCN have approximated the core-periphery structure with the final fit values around 0.3 during the observed time. Moreover, it can be noted that the size of the core is irregular during the examined period with a relatively large number of nodes in the core in 2009. This result tends to suggest that the stable collaborative relationships had not been formed and the project-based collaborative network was fragmented into many components in that year. The topology of PRCN plotted in Figure 4 also shows that the network ties are unevenly distributed among the investigated organizations. To quantitatively examine the uneven distribution of network ties in PRCN, the cumulative degree distribution $P(K)$ was analyzed. The collaborative network at the time point of 2017 is depicted in Figure 5 as an example. As illustrated by a straight line in the double logarithmic plots in Figure 5, the cumulative degree obeys a power-law distribution $P(K) = 6.617 \times K^{-1.844}$. The

"scale-free" nature is thus also characterized in PRCN during the time period.

In order to identify and characterize the prominent organizations in PRCN, both degree centrality and eigenvector centrality are calculated. Table 7 lists the top five ranked organizations in each indicator. The result of degree centrality reveals that design organizations and construction organizations have occupied most positions in the top-five ranked organizations in PRCN during the examined period, especially the local main contractors (e.g., C23, C27, and C13) and the local design consultants (e.g., D46 and D05). This suggests that local main contractors and local design consultants have played an active role in the BIM implementation practices in private construction projects over the observed time frames. There are also several local owners occasionally emerging in the top ranks (e.g., O37, O59, and O57). As to the prominent organizations with high eigenvector centrality, some local main contractors (e.g., C23 and C27) and local design consultants (e.g., D32 and D46) have been fixed in the top places, whereas a few local owners show up in top ranks only occasionally. It can also be observed that some organizations in PRCN have ranked highly both in degree centrality and eigenvector centrality (e.g., C23, C27, and D46). This result suggests that these active organizations with high degree centrality are also connected closely with each other and thus gain relatively high eigenvector centrality.

3.3. Results of the Comparative Analysis of the Network Characteristics of PUCN and PRCN.

The comparison of network structure indicators for PUCN and PRCN is illustrated in Figure 6. Figure 6(a) shows that the values of the linked node fraction in both networks have significantly increased during the examined period. But it also shows that there is a higher increasing speed in PUCN than that in PRCN. This result indicates that the relationships among the involved organizations in BIM-based construction projects in the public sector have been established faster than those in the private sector. As shown in Figure 6(a), there are also some organizations that have used BIM in construction projects in the private sector in 2009. However, the significant growth of BIM-based connections among the participant organizations in private project was observed until 2013. With regard to the average node degree, it is shown in Figure 6(b) that the value for PUCN displays a faster growth trend as compared with that for PRCN. This result indicates that the examined organizations in PUCN have more direct collaborative connections with each other (e.g., each organization was connected to more than seven others on average in 2017) than the examined organizations in PRCN (e.g., each organization was connected to more than four others on average in 2017). Similar difference can also be observed in comparison with the statistics of network density for PUCN and PRCN in Figure 6(c). These results could be explained in terms that construction projects in PUCN are usually complicated projects which need cooperation of multiple participants to complete (e.g., the mega subway projects), whereas construction projects in PRCN are mostly building

TABLE 6: Core-periphery structure in PRCN.

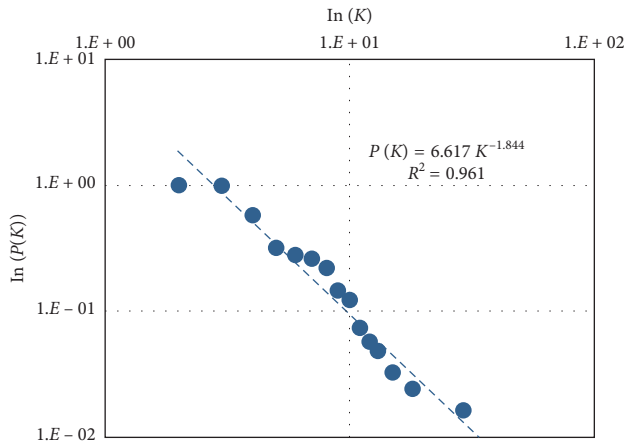| Time points	Density of linkages		Number of nodes in the core	Final fitness
	Core	Periphery		
2009				
Core	0.248	0.005	15	0.376
Periphery	0.005	0.003		
2011				
Core	0.667	0.04	7	0.373
Periphery	0.04	0.008		
2013				
Core	0.424	0.036	12	0.336
Periphery	0.036	0.012		
2015				
Core	0.281	0.043	20	0.291
Periphery	0.043	0.017		
2017				
Core	0.225	0.047	26	0.294
Periphery	0.047	0.018		

FIGURE 5: Power-law distribution of node degrees in PRCN in 2017.

TABLE 7: Five top ranked organizations in PRCN during 2009 to 2017.

Measure	2009	2011	2013	2015	2017
Degree centrality	C23	C23	D46	C27	D46
	O37	D46	C27	D46	C27
	D32*	C27	C23	C23	C23
	D46	D32*	D32*	D5	D5
	C61	D5	D5	D32*	C13
Eigenvector centrality	C23	D46	D46	C27	D46
	D46	D32*	C27	D46	C27
	O59	C27	D32*	D32*	D32*
	D32*	C23	C23	C23	O49
	C27	O49	O49	O49	C23

The capital letter in the code of the organizations represents the organization type (O refers to owners, D refers to design consultants, and C refers to main contractors), and the second digit represents the serial coding number for each organization type. The asterisked organizations are overseas organizations, whereas the nonasterisked are local organizations. For example, D32* refers to the design consultant which is coded as No. 32 among all the design consultants and it is an overseas company/organization, while O37 refers to the owner which is coded as No. 37 among all the owners and it is a local company/organization.

construction projects of which the construction procedure and organization structure are both relatively simple. The results in Figures 6(d) and 6(e) further illustrate that while the average distance among nodes in the main component for PRCN is longer than that for PUCN, the clustering coefficient for PRCN is smaller than that for PRCN. Additionally, the comparison of graph centralization for PUCN and PRCN in Figure 6(f) also shows that the increasing trend of graph centralization for PUCN is more significant than that for PRCN. It can also be observed intuitively in Figures 2 and 4 that despite the relatively small network size, PUCN has more "centered" nodes (i.e., the specifically large nodes in the networks) than PRCN. It could help explain why the increasing trend of graph centralization for PUCN slows down in the latter period. Moreover, a difference also exists when individually characterizing the roles and attributes of the prominent nodes (the top-five ranked organizations) in each examined network. It shows that the local public owners play a leading role in the evolution of PUCN, and several international designers are also active in the collaborative network. It also shows that local design consultants and the local main contractors stand out to make an active contribution to the network development of PRCN. Taken together, these results tend to suggest that organizations generally have more frequent and denser project-based collaborative ties for BIM implementation with others in the public sector than in the private sector. This probably could be explained by the influence of government policies or the BIM implementation efforts of some large public owners (e.g., HA).

3.4. Associations between the Evolution of PUCN and PRCN.

It is revealed in the above comparative analysis that certain owner organizations have played leading roles in PUCN, while certain design organizations and construction organizations (especially local contractors) have played relatively active roles in PRCN. In order to identify the associations between the two examined networks, this study statistically characterizes the performance of the design and construction organizations in both collaborative networks.
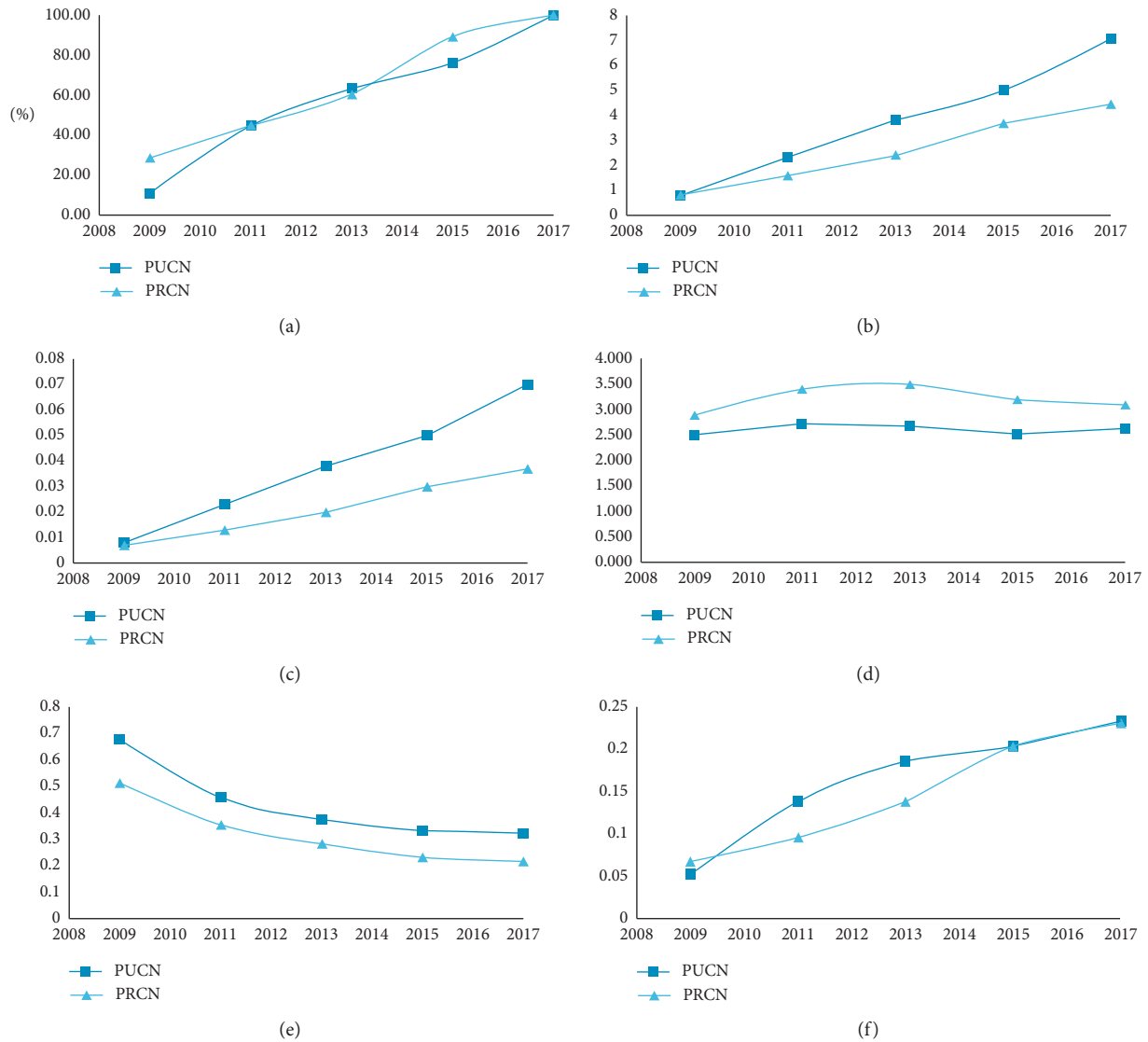
FIGURE 6: Comparisons of network indicators between PUCN and PRCN. (a) Linked node fraction; (b) average degree; (c) network density; (d) average distance in main component; (e) clustering coefficient; (f) graph centralization.

TABLE 8: Top three organizations for degree rank in PRCN.

Time points	2009	2011	2013	2015	2017
	C23 (NA)	C23 (2)	C27 (7)	C27 (7)	C27 (8)
Top three organizations for degree in PRCN	C61 (NA)	C27 (2)	C23 (2)	D46 (6)	D46 (9)
	D46 (NA)	D46 (1)	D46 (3)	C23 (2)	C23 (2)

The number in parentheses after the coding of each organization represents the organization's rank in PUCN of the last examined period, for example, C23 (2) in PRCN in 2011, where 2 refers to the organization C23 ranked second in PUCN in 2009.

According to the statistics of the network nodes, the number of nodes coexisting in PUCN and PRCN in each discrete time period has increased from 9 in 2009 to 29 in 2017. It suggests that an increasing number of design and construction organizations are involved in both public projects and private projects, and thus the BIM experience could be shared in both collaborative networks. Furthermore, in PRCN, the percentage of design and construction organizations who have participated in PUCN formerly has increased steadily from 9.02% in 2011 to 20.49% in 2017 (a time lag effect was taken in analysis of the association between the two networks, so the start time is 2011). Moreover, the degree of the design organizations and the construction organizations is individually calculated and examined for both PUCN and PRCN. It is worth noting in Table 8 that with regard to the degree of the design and construction

organizations in PRCN, the top three organizations are quite stable (i.e., C23, C27, and D46), and all these organizations have previously involved in PUCN since 2009. Together, these findings indicate that a growing number of design and construction organizations, who have involved in PUCN in early periods, have acted as the leaders in PRCN in latter periods.

4. Conclusion

Using the dynamic network perspective and a longitudinal data set of BIM-based construction projects in Hong Kong during 2002–2017, this study aims to quantitatively characterize how the structural characteristics of PUCN and PRCN evolve differently over time. This study also explores how these two networks relate to each other during the evolution process. The descriptive analysis results provide evidence that both collaborative networks become increasingly dense over time. However, the two examined networks persistently exhibit small-world properties and the core-periphery structure with a small number of super-connected star organizations. The comparative analysis results reveal that there is a more significant trend in the increasing closeness and centralization around some high-status organizations involved PUCN. The results also suggest that when characterizing the key organizations in the evolution of both networks, local owner organizations and overseas design organizations contribute more actively in PUCN, whereas local design organizations and local construction organizations contribute more actively in PRCN. Furthermore, those local design and construction organizations who have gained BIM experience in PUCN in early periods tend to be influential to the formation of PRCN in later periods. The results could provide a dynamic network view of how industry organizations interact with each other in BIM implementation practices across different types of projects. The findings also contribute to a deepened understanding of how relationship networks can be managed to facilitate the diffusion of innovations like BIM in the project-based construction industry.

The findings of this study also have several managerial and policy implications. Considering the tendency of expanding around certain "star" nodes in both PUCN and PRCN, this study suggests design consultants and main contractors to act fast to possess advantaged network positions in the industry. And therefore, they could gain long-term organizational competitiveness in BIM practices. In addition, due to the important role of certain local design and construction organizations in the diffusions of BIM technology, government should encourage these organizations to further facilitate BIM implementations in the regional industry.

Despite its theoretical contributions and practical implications, this study still has several limitations. The research restricts its analysis to a specific collaborative network for BIM implementation in Hong Kong, which may limit the generalizability of the empirical results on network dynamics to other institutional and cultural contexts. Future research could further conduct cross-cultural studies to validate or expand the findings presented in this study. Furthermore, limited by the data collecting process, this study only focuses on the collaborative relationships among owners, designers, and contractors. Future studies could include other project participant organizations (e.g., consultants) in the analysis. It will provide a more comprehensive understanding of how different types of organizations interact with each other in BIM implementation practices across projects in the construction industry.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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