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Analyzing collaborative relationships among industrialized construction technology innovation organizations: A combined SNA and SEM approach

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ABSTRACT

Industrialized construction technology (ICT) is widely used and becoming the new green construction method, but its development is being hindered by lack of innovation. To improve this, stakeholders are endeavoring to develop more innovative methods by inter-organizational collaboration. Despite its extensive use by other industries such as manufacturing, little is known of how to successfully apply collaborative innovation to ICT. This paper develops a method for studying the effects of a variety of aspects of existing collaborative relationships for ICT innovation using a combination of social network analysis (SNA) and structural equation modeling (SEM). A set of hypotheses are proposed concerning the expected influence of SNA factors of interaction frequency, emotional intensity, reciprocal exchange, network size, network density, centrality, relationship strength, network position, promotion, enterprise scale, nature and experience on collaborative innovation. Using questionnaire data obtained from a large sample of practitioners, SEM is then used to identify the key indicators involved and the extent of their effects on innovation. The paper constructs a collaborative ICT innovation relationship model in which the strengths of the interaction paths between stakeholders are obtained. With a single exception, this confirms all the hypotheses. Most of the SNA-based *a priori* hypotheses are shown to be well supported, which indicates the suitability of the SNA concept in developing collaborative ICT innovation. SNA is therefore confirmed as providing a suitable conceptual basis for the modeling and analysis of ICT innovation relationships. From this, a set of recommendations are provided to guide operating companies, designers and contractors in improving their collaborative innovation efforts. The results enable suggestions for enhancing collaborative ICT innovation capacity to be advanced to promote the interaction between stakeholders and the occupation of strategic positions. Although the study is carried out in the context of China's prefabricated housing construction, the methods can be adopted in the broader global community.

1. Introduction

Industrialized construction technology (ICT) is widely used in several countries and regions around the world, including Japan, the United States, Europe and China (including Hong Kong), relying on the innovative use of solar energy systems, maintenance of natural external insulation systems, high-quality, performance and highly flexible industrial internal facilities and products, etc., (Liu et al., 2012)., and inevitably involves a high degree of prefabricated components (Pizzi et al., 2012).

However, the construction industry is well-known for its low level of innovation (e.g., Noktehdan et al., 2015) due to the one-of-a-kind nature of its projects, site production, temporary multi organizations and regulatory intervention (Koskela and Vrijhoef, 2001), resulting in the new industrialized building method having low integration and inferior quality components due to poor

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construction technology standards and security systems.

This is attributable to the difference between construction innovation and traditional innovation as exemplified by the manufacturing industry (Slaughter, 2000). As a project-based industry, construction involves many participants, with each party being an independent organizational entity chasing its own interests and perceived incentives from the project (Ofori and Moonseo, 2006) and playing different functional roles in the innovative process. The solution to the industry's innovation problem therefore is to overcome these differences by greater collaboration of those involved by what has been termed *collaborative innovation relationships* (Gilson et al., 2009).

The optimizing of collaborative relationships among construction innovation organizations can prompt construction innovation development. A construction organization must possess all the prerequisite resources needed to adopt a novel technology and optimizing collaborative relationships can drive the decision to adopt such a technology (Nikas et al., 2007). The construction industry, professional organizations and the government need to form a broad collaboration in order to develop competent professionals (Toor and Ofori, 2008). Although collaborative relationships can prompt construction innovation development, there is a lack of widely accepted indicators and criteria to assess the performance of collaborative designs (Ren et al., 2013).

Progress to date in forming such relationships has been slow. Stakeholders of industrialized building, for example, have initially established a union of collaborative innovation but little is known of its success in providing innovations or of the influence of different aspects of the relationships involved. Social network analysis (SNA) offers a potential means of studying such influences on innovation in terms of interaction frequency, emotional intensity, reciprocal exchange, network size, network density, centrality, relationship strength, network position, promotion, enterprise scale, nature and experience. From such an analysis, if appropriate, it is then possible to maximize the innovation obtained by inter-organizational collaboration in promoting the performance of ICT and thus enhancing the development of the industrialized construction process.

This paper approaches this by a combination of social network analysis (SNA) and structural equation modeling (SEM). First, a set of hypotheses are proposed that are concerned with the likely influence of SNA's interaction frequency, emotional intensity, reciprocal exchange, network size, network density, centrality, relationship strength, network position, promotion, enterprise scale, nature and experience on ICT collaborative innovation. SEM is then used with questionnaire survey data in the context of Chinese industrialized residential building projects, which indicates that SNA provides a suitable conceptual basis for collaborative ICT innovation and the key factors involved. Based on this, suggestions are made to investigate these and other collaborative innovation activities within a particular range from a specific stage of industrialized building; the impact of stakeholder behavior; and the development of a simulation system of collaborative ICT innovation relationships to better understand the synergistic aspects of the innovation processes involved. A set of recommendations are also provided to guide BIM experts, operating companies, designers and contractors on how to improve their collaborative innovation to further promote the adoption of ICT in China and the global community generally.

2. Literature review

2.1. Industrialized construction

Previous research investigates industrialized construction mainly from the perspectives of technology, environment and organization, focusing on the development of industrialized building systems, sustainable building industrialization and the development status of construction technological innovation.

From a *technology perspective*, prefabrication is seen as the first step towards industrialization in seeking innovative processes to simplify industrialized building systems (Richard, 2005) and is therefore becoming increasingly important in their development. Prefabrication involves the off-site prefabrication of components for assembly on site and has been the subject of many studies (see Ezcan et al., 2013; for a review of recent work), with well-known potential benefits of economies of scale, enhanced quality control and improved efficiency. Industrialized building systems representing the prefabrication concept have been widely investigated by practitioners and researchers in Malaysia for example (Hamid et al., 2008).

Many innovative digital technologies, such as Global Position Systems (GPS) and Radio Frequency Identification (RFID), are also being effectively applied in construction management (Li et al., 2014) - accelerating the development of industrialized construction. However, the construction industry has a low integration of industrialized technologies such as automation, standardization and modularization (UNEP Report, 2002). Improving the level of customization can affect the operational performance of plant and stakeholder satisfaction with industrialized construction (Nahmens and Bindroo, 2011).

From an *environmental perspective*, industrialized construction can reduce waste and the use of energy (Chen et al., 2010). Sørensen and Torfing (2011), for example, have studied industrialization in construction in relation to sustainability and energy use to compare the difference between sustainability and industrialization and identify possible synergies and barriers in proposing a strategic research agenda for future energy efficient construction management. Wandahl and Ussing (2013) also discuss the common characteristics of sustainable industrial construction, synergistic effect, sustainability of industrial construction management and energy issues.

From an *organizational perspective*, the determination of the precast manufacturing site is important in endorsing the use of an industrialized construction system (Mohamed et al., 2013). Golob et al. (2012) believe it is essential to link the functions of project management and marketing management for organizations to be successful in the construction industry (Golob et al., 2012). Zhang et al. (2015) find that embedding "green" in project-based organizations is particularly problematic due to the increased conflict between the organization-wide change initiatives and emerging cost occurring during daily operation (Zhang et al., 2015). Jalal and Koosha (2015) have also studied different organizational contextual and structural dimensions, and found 29 organizational context variables which are thought to have a decisive impact on the characteristics of project management offices (Jalal and Koosha, 2015).

2.2. Collaborative innovation

Collaborative innovation is a core component of current innovation theories. After years of evolution, it has become a widely acknowledged new techno-economic paradigm. Derived from considerable domestic and international experience, collaborative innovation involves the sharing of various innovation elements within and between enterprises. Collaborative innovation can be divided into internal and external collaboration. Internal collaborative innovation studies the interaction mechanisms of interrelated core elements (technology and market) and several supporting elements, including inter-organizational collaborative innovation mechanisms (Burg et al., 2014; Davis and Eisenhardt, 2011) and influencing factors and effects (Sørensen and Torfing, 2011) from a microeconomic perspective.

Enterprise innovation behavior beyond the boundary of the organization has become increasingly open (Gulati and Gargiulo, 1999) in the form of Cross-Boundary Spanning cooperative behavior (Hsiao et al., 2012). Ketchen et al. (2007) propose collaborative innovation to be 'the creation of innovations across firm (and perhaps industry) boundaries through the sharing of ideas, knowledge, expertise and opportunities'. With the continuous development of innovation openness, successful innovation requires different disciplines, levels and types of organizations, prompting many studies of external collaborative innovation.

The realization of external collaborative innovation mainly depends on the interaction of industrial organizations and other stakeholders from both lateral and longitudinal dimensions. Lateral collaborative innovation mainly refers to the collaboration of stakeholders of the main industry segments in the same industrial categories, and mainly involves the study of the lateral collaborative innovation patterns involved (Aldrich and Sasaki, 1995; Dickson and Weaver, 1997) and their effects on performance (van der Valk et al., 2011). Longitudinal collaborative innovation mainly refers to the collaboration of the main industry stakeholders in different aspects of the same functional chain, mainly from the perspective of the supply chain, researching collaborative innovation models between enterprises, customers, brokers and longitudinal related elements (Chapman and Corso, 2005), income distribution, innovative ability (Swink, 2006) and other factors (Greer and Lei, 2012).

Collaborative innovation is a practice that relies on the involvement of various stakeholders (McAdam et al., 2008). Internal and external collaboration needs the active interaction of multidimensional stakeholders to achieve the collaborative innovation of information, objectives, performance and organizational factors. Most inter-organizational collaborative innovation is government-oriented (Safford et al., 2009) so that, by comparing government organizations, stakeholders can better identify the research priorities of socio-economic factors. The major characteristics of collaborative innovation are that stakeholders have a unified upper target, common motivation and cost-efficient communication to achieve frequent communication and multidimensional cooperation by taking advantage of various innovation-development platforms. Collaborative innovation differs from the simple coordination and cooperation of original innovation, as it needs to build innovation networks to achieve maximum integration of the innovative elements. Therefore, the core concept of collaborative innovation can be summarized as involving the following factors: a common goal of innovation activity; nonlinear interaction between the main participants; complementary benefits between elements and entities; and achieving overall relative stability.

2.3. Collaborative technological construction innovation

Construction is a project-based industry with many participants, each being an independent organizational entity chasing its own interests and perceived incentives from the project (Ofori and Moonseo, 2006) and playing different functional roles in the innovative process. The construction supply chain is also highly dispersed in which knowledge, materials, technology and other factors spread across several different issues (Bernstein et al., 1998).

The opportunities for inter-organizational collaboration are therefore perceived by many as being rare, concentrating instead on the individual efforts of those involved. Dulaimi et al. (2003), for example, propose that a project manager should have the ability to champion innovation. The government can also act as a sustainable technology broker in the market and stimulate innovation by financial and legal means and R & D funded activities, and plays an important role in the promotion of technological innovation in building (Foxon, 2014). Owners can play an important role in the innovative process in promoting the integration of construction project participants by creating an innovation atmosphere as a participant and project leader, but often avoid technological innovation in order to seek short-term returns and prevent the extra costs and risks involved. Suppliers can also play an important role. Pries and Dorée's (2005) statistical analysis of 20th century Dutch construction innovation, for example, found approximately 2/3 of innovations are by suppliers. In addition, construction material and equipment suppliers are major investors of R&D in the UK construction industry, whose R&D costs have substantially increased over the years, while R&D costs have decreased in the construction industry generally.

However, several studies have shown that collaboration between construction organizations is an effective approach for improving efficiency and encouraging innovation. Blayse and Manley's (2004) research, for example, shows the importance of supply chain integration in promoting innovation, mainly in the procurement process. Successful innovation is also recognized as requiring effective cooperation between departments, with partnerships being realized through the supply chain (Berkout et al., 2006). Additionally, previous research indicates that collaboration has a significantly positive relationship with the performance of construction projects, which goes beyond the construction period, cost and quality control to encourage creativity and enhanced user-satisfaction. The systemic integration capabilities, close collaboration and open communication involved in these projects are considered major factors for successful innovation (Dulaimi et al., 2003). Improving design collaboration capabilities in the initial-phase helps in acquiring higher environmental performance and innovation capacity. Encouraging and supporting the implementation of innovative solutions, such as the establishment of high-quality structures, high process-performance and collaborative mechanisms between project stakeholders, can help improve the innovation capability of construction technologies. Improving the technical and knowledge management capabilities of the participating parties through organization power can achieve integrated goals. The level of utilization of innovation results needs the coordination of owners, design units, contractors, subcontractors and other stakeholders. Implicit coordination includes informal negotiation and cooperation, information exchange and coordination. In contrast, explicit coordination includes specialized changes, signatures for risk and uncertainty acceptance and disclaimers for time delays.

A lack of collaboration capacity and overall concept of design and construction on the other hand can prolong the construction period and reduce innovation capacity (Rutten et al., 2009). Similarly, a lack of coordination mechanisms can complicate the innovation process and increase communication costs. Dewick and Miozzo (2004), for example, study the relationship between innovative construction organizations based on sustainable technology diffusion problems in Scotland, noting that the lack of coordination in pursuing the interests of all stakeholders hinders the introduction of innovation.

As collaborative innovation continues to spread in all fields, its application in the construction industry is gradually increasing. In contrast with inexperienced owners, many experienced owners recognize this need and establish long-term and stable relationships with designers and contractors in order to reduce the costs caused by short-term cooperation, and increase the return of innovative technologies. The innovation process is receiving more attention with one-off, high-value and engineering-intensive projects.

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Table 1
Definition of model variables.

Variables		Definition
Explained or dependent variable	Technological innovation	Applying the results of cost and time reduction, quality improvement and related technology patents in the process of ICT.
Explanatory variables	Interaction frequency	Communication time between two stakeholders per unit time.
	Emotional intensity	Depth of emotional connection between stakeholders.
	Reciprocal exchange	Exchange of technologies, resources and information for the mutual benefit of stakeholders.
	Network size	Number of stakeholders in the network.
	Network density	Ratio of the number of edges in the network to the maximum number possible - namely the tightness of relationships between stakeholders.
	Centrality	Mediator role and importance of the nodes in the network, as well as the observation of information flow.
Mediator variables	Relationship strength	Strength of the relationships between stakeholders.
	Network position	Position of the stakeholders in the network and their significance, behavioral characteristics, network density, centrality and other characteristics having an influence on stakeholders.
	Promotion	Favorable conditions for stakeholders to understand and apply construction technologies, including relevant state policies, industry standards, corporate training activities etc.

To further promote construction innovation, Shapira and Yehiel (2011) proposes collaboration between industry and academia by establishing an innovative platform to integrate the resources and talent of educational institutions and industry (Aouad et al., 2010). Based on original research, Xue et al. (2014), after reviewing and analyzing the literature, also present a conceptual framework for construction innovation, emphasizing the critical role of collaboration. This has led Park et al. (2004), for example, to propose a construction dynamic innovation model based on system dynamics, which includes multiple individual and situational impact factors and emphasizes the correlation between two key factors that drive construction innovation. They use an example of a project in Singapore for their empirical research and discuss how the application of their model promotes construction innovation.

3. Research hypotheses

Previous studies have shown that ICT innovation performance is influenced by the strength of relationship between the stakeholders, their position in the technology innovation network and their promotion (Ofori and Moonseo, 2006; Berkout et al., 2006; Rutten et al., 2009; Foxon, 2014). Technological innovation is selected as the explained or dependent variable, with the mediator variables including relationship strength, network position and promotion. Relationship strength can be explained by the stakeholders' frequency of interaction, emotional intensity and reciprocal exchange (Dewick and Miozzo, 2004; Chapman and Corso, 2005; McAdam et al., 2008) and network position can be described by network size, network density and centrality (McAdam et al., 2008; Safford et al., 2009). Therefore, there are six explanatory variables, comprising interaction frequency, emotional intensity, reciprocal exchange, network size, network density and centrality.

In developing the research hypotheses, some definitions of the variables involved are listed here. Firstly, structural equation models comprise four types of variables (Xiong et al., 2015):

(1) ***Explained or dependent variables*:** comprise the collaborative innovation performance of ICT (referred to as 'technological innovation' in the model).
(2) ***Explanatory variables:*** comprise interaction frequency, emotional intensity, reciprocal exchange, network size, network density and centrality.
(3) ***Mediator variables*:** comprise relationship strength, network position and promotion. The variables act as mediators in the relationship between the explanatory variables and the dependent variable.
(4) ***Moderator variables:*** comprise enterprise scale, nature and experience. These have a potential or direct impact on the interactions between variables.

These are summarized in Table 1 in terms of SNA-based ICT collaborative innovation.

3.1. Interaction, frequency and emotional intensity

Research into network relationships suggests that the three dimensions of interaction frequency, emotional intensity and reciprocal exchange act as relationship variables that directly affect relationship strength in collaborative innovation. Moderator variables also have various degrees of impact on the relationships between the three dimensions and relationship strength. Previous studies indicate that small-scale enterprises, non-state-owned enterprises and those that lack experience tend to build weakly tied collaborative innovation networks. It is generally believed that smaller-scale enterprises and inexperienced stakeholders, more concerned with the effects of interaction frequency on relationship strength and the nature of the enterprise, affect the significance of the relationship between interaction frequency and relationship strength. Larger-scale enterprises and inexperienced stakeholders, on the other hand, are thought to pay more attention to the effects of reciprocal exchanges on relationship strength. This suggests the following hypotheses:

H1. Interaction frequency affects relationship strength.

H1a. Interaction frequency affects relationship strength, and the smaller is the enterprise size, the more significant is the relationship between stakeholders.

H1b. Interaction affects relationship strength, and is more significant between non-state-owned stakeholders.

H1c. Interaction affects relationship strength and is more significant between stakeholders who are less experienced.

H2. Emotional intensity affects relationship strength.

H3. Reciprocal exchange affects relationship strength.

H3a. Reciprocal exchange affects relationship strength and the larger is the enterprise scale, the more significant is the relationship between stakeholders.

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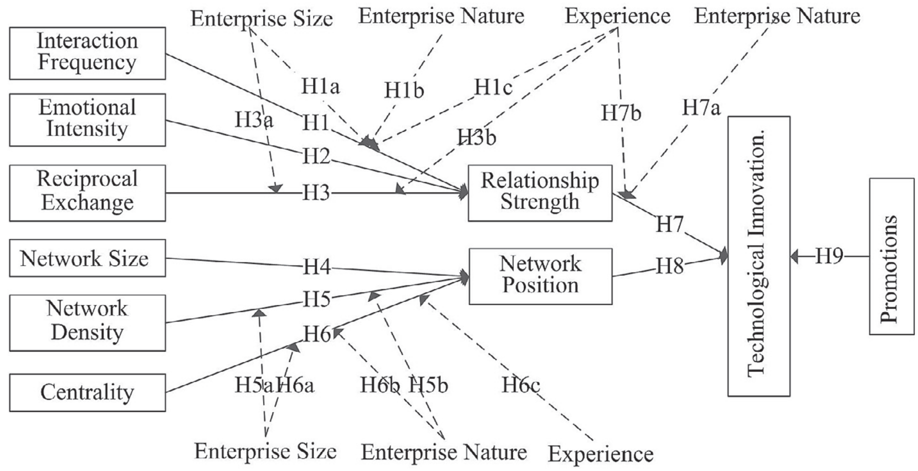

Fig. 1. Collaborative ICT innovation relationship measurement model.

H3b. Reciprocal exchange affects relationship strength and is more significant between stakeholders who are less experienced.

3.2. Structure variables and network position

Network structure is concerned with the network position of stakeholders and the benefits derived from that position. Network position changes with the evolution of network size and density, and the higher the centricity that stakeholders have the more important is the network position. Moderator variables also have various degrees of impact on the relationship between structure variables and network position. It is generally accepted that the stakeholders of larger-scale enterprises pay more attention to obtaining benefit from their network position and corporate nature affects the significance of the relationship between network density and position. It is also generally considered that the performance of smaller-scale enterprises, state-owned enterprises and experienced stakeholders is greater when centrality affects network position. Therefore, the next hypotheses are:

H4. Network size affects network position.

H5. Network density affects network position.

H5a. Network density affects network position and the larger is the enterprise scale, the more significant is the relationship between stakeholders.

H5b. Network density affects network position, and is more significant between state-owned stakeholders.

H6. Centrality affects network position.

H6a. Centrality affects network position, and the smaller is the enterprise size, the more significant is the relationship between stakeholders.

H6b. Centrality affects network position, and is more significant between state-owned stakeholders.

H6c. Centrality affects network position, and is more significant between experienced stakeholders.

3.3. Relationship strength and technological innovation

The analysis of network relationships reveals that relationship strength plays an important role in the transfer and exchange of knowledge and information throughout the network. Dissemination of knowledge often occurs with stakeholders in strong relationships. Generally, non-state-owned enterprises and experienced stakeholders pay more attention to the influence of relationship strength in collaborative ICT innovation. Therefore, the hypotheses are:

H7. Relationship strength affects technological innovation.

H7a. Relationship strength affects technological innovation and is more significant between non-state-owned stakeholders.

H7b. Relationship strength affects technological innovation and is more significant between experienced stakeholders.

3.4. Network position and technological innovation

Network position has a positive role in promoting technological innovation. Different network positions affect the capabilities of corporate identity, access and use of information technologies from the network. An appropriate network position can help enterprises gain better access to resources and explore valuable information (Uzzi, 1997). Thus the hypothesis is:

H8. Network position affects technological innovation.

3.5. Promotion and technological innovation

Promotional activities comprise factors that can directly affect technological innovation, such as government policies, industrial standardization and risk control, and have a significant effect on collaborative ICT innovation. The formation and implementation of industrial standardization documents provide the most direct guidance for technological innovation and corporate risk control largely affects the absorption and adoption of new construction technologies. Thus the hypothesis is:

H9. Promotions affect technological innovation.

The model assumptions therefore include relationship assumptions and moderator assumptions and integrating the specific research hypotheses with a collaborative innovation measurement model can help in obtaining the final model. The unidirectional arrows of this model (except the moderator variables) shown in Fig. 1 start from the independent variables and end at the dependent variables, implying that the independent variables affect the dependent variable.

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4. Data collection

Industrialized construction manufacturing facilities have expanded to a reasonable scale in some cities in East China, such as Nanjing and Nantong. Such industrialized facilities mainly produce concrete shear walls, laminated slabs, frame columns, beams and other precast components that are extensively used in the construction of affordable housing. Beijing, Shanghai and other first-tier cities, Guangdong, Anhui and other developed provinces, and China's northeastern region have increased their efforts to promote the development and application of the industrialization of assembled monolithic structures. The central government and some provinces have issued associated technical standards and industrialized construction codes.

Currently, developers, construction units and general construction contractors in China are mostly interested in prefabricated housing. These include, for example, Nanjing Dadi's "prefabricated prestressed assembled monolithic concrete frame structure"; Beijing Vanke's "assembled monolithic shear wall system"; Nantong Construction's "all prefabricated assembled monolithic shear wall system"; Taiwan Runtai's "prefabricated assembled frame structure"; and Shenyang Yuhui's "prefabricated assembled monolithic concrete shear wall".

Our analysis uses precast concrete (PC) residential construction technology as the background to study collaborative innovation, social networks and innovation ability. As relevant data cannot be accessed directly, a questionnaire survey was conducted to collect network relationship data. Enterprises with an early exposure to industrialized construction were mainly selected as key survey respondents. These include Vanke, LongFor, Broad Homes, Shanghai Urban Construction, Shanghai Construction Engineering, Beijing Construction Engineering, Greentown Decoration, China State Construction Engineering System and Libby.

Based on previous research, practitioner advice was combined with other resources for the questionnaire design and data collection. In designing the questionnaire:

(1) A large amount of relevant literature was systematically reviewed, from which widely accepted concepts and authoritative ideas were considered, in producing the first draft of the questionnaire.
(2) Several experts were then invited to give suggestions concerning the questions used, the logical relationships between variables and the format arrangement. This resulted in expressions that were too academic and technical being removed to increase the practicability of the second draft of the questionnaire.
(3) Pilot tests with practitioners were next conducted. The questionnaire was sent to several relevant staff working in the enterprises targeted for the main study and its validity was tested based on their answers.

In order to maximize the objectivity and authenticity of the questionnaire and the data, much attention was paid to the current situation in China to ensure the questionnaire's relevance to the latest industrialized construction developments. The questionnaire aimed to solicit:

(1) Basic information. Respondents were requested to provide both personal information and information concerning their workplaces. The personal information includes workplace, length of service, education level and position. The information concerning workplace includes the corporate size and nature of their companies, business attributes and other basic information associated with ICT.
(2) Details concerning the main influencing factors in collaborative ICT innovation relationships - interaction frequency, emotion intensity, reciprocal exchange, network density, centrality and promotions.

A five-point Likert scale was used to evaluate the variables, where 1 and 5 denote "strongly disagree" and "strongly agree" respectively.

Respondents were limited to experienced staff or senior managers as they are more familiar with the internal situation of their companies and can answer the questions effectively. It was intended to collect a large number of responses; however, the literature suggests that the response rate was likely to be low. Therefore, convenience sampling was made and the questionnaire was distributed mainly via internet through associations, consulting firms and friends to ensure a reasonable collection time and quality of the data. The region, the nature and size of enterprises sampled were deliberately diversified to obtain a wider spread of responses as possible.

Ultimately, 190 digital and 18 paper responses were received. 23 responses with obvious problems were treated as invalid, reducing the sample to a total of 185 responses. Several responses containing missing data were received but made acceptable by use of the mean substitution method in the analysis.

The data are analyzed by a combination of SNA and structural equation modeling (SEM). SEM is used with the questionnaire survey data, which indicates that SNA provides a suitable conceptual basis for collaborative ICT innovation and the key factors involved (Xiong et al., 2015). There is no general consensus on the sample size, N, needed for SEM. Typical suggestions are that N should be as big as possible, $N/p > 10$ (where p is the index value), or between 100 and 200, and that when N is small, the index value of variables can be increased to improve stability. The sample size here was therefore taken to meet the usual SEM requirements.

The data was collected via internet, with experienced staff or senior managers selected as respondents who can accurately

Table 2
Summary of descriptive statistics.

Variables	N	Mean	Std dev	Var	Kurtosis	Skewness
IF1	185	3.8162	0.92593	0.857	−0.788	0.801
IF2	185	3.8649	0.90776	0.824	−0.698	0.448
IF3	185	3.9189	0.90825	0.825	−0.851	0.923
EN1	185	4.0432	0.79964	0.639	−0.401	−0.535
EN2	185	4.0432	0.78593	0.618	−0.620	0.515
RE1	185	3.8324	0.83992	0.705	−0.453	0.022
RE2	185	4.1027	0.85035	0.723	−0.842	0.529
RE3	185	3.5514	0.09783	0.205	−0.182	−0.912
RE4	185	4.1946	0.81091	0.658	−0.927	0.876
NS1	185	3.8378	0.98117	0.963	−0.471	−0.472
ND2	185	3.7892	0.70240	0.493	−0.442	0.340
ND3	185	3.7297	0.79566	0.633	−0.457	0.266
CEN1	185	3.7514	0.97958	0.960	−0.605	0.285
CEN2	185	3.8595	0.90393	0.817	−0.700	0.476
CEN3	185	3.7297	0.87999	0.774	−0.555	0.604
TS1	185	3.9135	0.82954	0.688	−0.587	0.285
TS2	185	3.9135	0.82296	0.677	−0.252	−0.656
TS3	185	3.9892	0.87221	0.761	−0.774	0.597
NP1	185	3.9784	0.92640	0.858	−0.537	−0.253
NP2	185	3.9622	0.95762	0.917	−0.712	−0.043
NP3	185	3.6595	0.69761	0.487	−0.392	0.109
FC1	185	3.1189	0.81222	0.660	0.024	0.260
FC2	185	3.0270	0.82378	0.679	−0.050	0.230
FC3	185	3.3351	0.83152	0.691	−0.467	0.115
TI1	185	3.2757	0.92355	0.853	−0.535	0.122
TI2	185	3.2270	0.95116	0.905	−0.278	−0.528
TI3	185	2.8000	0.96007	0.922	0.411	−0.690
TI4	185	2.9081	0.94822	0.899	0.108	−0.572

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Table 3
Rotated component matrix.

	Components					
	1	2	3	4	5	6
IF1	0.633	0.222	0.033	0.071	−0.049	−0.016
IF2	0.646	0.427	−0.034	−0.119	0.172	0.182
IF3	0.642	0.367	−0.001	0.012	0.027	0.212
EN1	0.737	0.005	−0.020	0.229	0.058	0.090
EN2	0.696	0.016	0.002	0.233	0.085	−0.085
RE1	0.547	0.121	−0.092	0.137	0.114	0.163
RE2	0.542	0.128	0.147	0.185	−0.026	0.246
RE3	−0.010	0.830	0.088	0.018	−0.025	0.149
RE4	0.451	0.477	0.034	0.183	−0.105	0.211
NS1	0.265	0.674	0.180	0.282	0.011	0.112
ND2	0.425	0.302	0.199	−0.156	0.154	0.613
ND3	0.411	0.350	0.108	−0.309	0.121	0.527
CEN 1	0.183	0.383	0.284	0.135	0.066	0.732
CEN 2	0.344	0.212	0.165	0.161	0.074	0.596
CEN 3	0.182	0.176	0.008	0.242	0.027	0.781
TS1	0.223	0.124	−0.015	0.687	0.093	0.369
TS2	0.159	0.311	-o.007	0.706	−0.018	0.165
TS3	0.246	0.154	0.079	0.486	0.603	−0.051
NP1	0.251	0.081	0.002	0.300	0.720	0.036
NP2	0.360	0.107	0.096	0.140	0.663	0.059
FC1	0.076	−0.078	0.262	0.160	0.747	0.093
FC2	0.010	−0.021	0.388	0.136	0.731	−0.043
TI1	0.162	0.264	0.633	−0.067	0.157	0.330
TI2	0.148	0.115	0.823	0.096	0.016	0.091
TI3	−0.112	−0.079	0.795	−0.063	0.273	−0.084
TI4	0.033	0.113	0.826	0.025	0.191	−0.098

Extraction method: PCA; Rotation: Varimax rotation standardized by Kaiser (rotation is convergent after the eighth iteration); cumulative variance contribution: 61.65%; KMO statistic: 0.872 (very acceptable); Bartlett's Test of Sphericity probability: 0.000).

answer the questions. The sample size is 185, which also meets the usual SEM requirements. Unbiased results can be guaranteed through the sampling approach used, which meets the need for sufficient face validity.

5. Results

5.1. Descriptive statistics on sample data

Descriptive statistics of the sample data are classified, processed

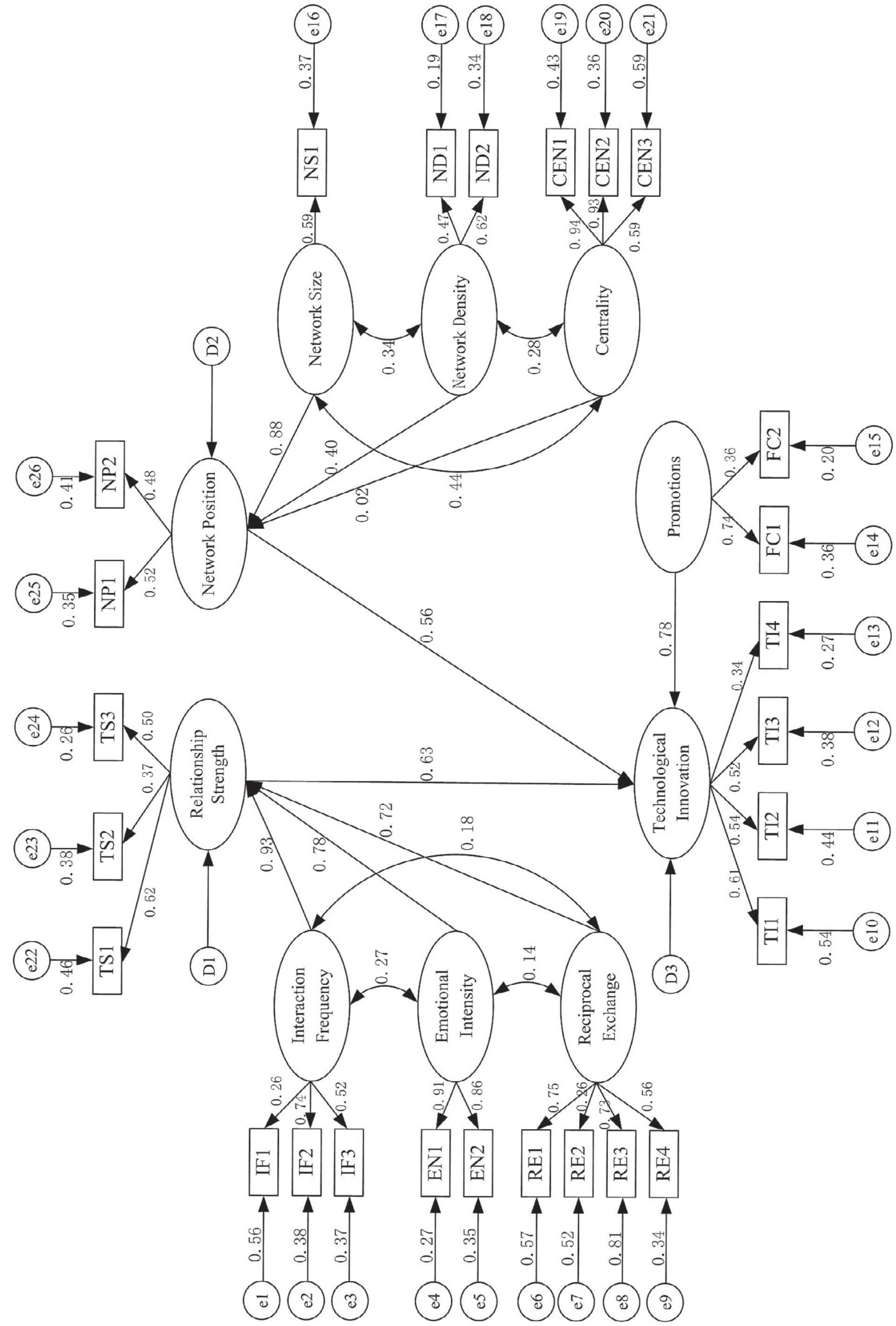

Fig. 2. Collaborative ICT innovation relationship model.

or represented in visual form, which are used to describe and analyze data features and variable relationship. The basic characteristics of the sample data are shown in Table 2. The use of a 1–5 Likert scale tends to produce a smaller standard deviation and variance for high and low means and a reduced absolute skewness. The majority of variables have a negative coefficient of kurtosis, possibly caused by the similarity of the respondents.

5.2. Pretests

Pre-Principal Component Analysis (PCA) tests show that, except for NP3 and FC3, the reliability of the variables meets the requirement of Cronbach's α>0.700. Removing NP3 and FC3 results in Cronbach's α of 0.768 and 0.741 for network position promotions respectively, indicating a satisfactory reliability for the remaining variables once NP3 and FC3 are omitted. Using PCA to carry out the factor analysis, the rotated component matrix is shown in Table 3.

The indices are therefore classified into six corresponding factors according to the criterion that the factor loading be larger than 0.50. Each index matches only one of the biggest common factors of the loading values. The extraction details are shown in Table 3 footnote. Overall, the analysis above illustrates that the sample data meets the basic requirements for SEM.

Table 4
Model parameter estimations and the significance level.

Effect relationship between variables			Standardized regression coefficients	P
Relationship strength	<–	Interaction frequency	0.172	**
Relationship strength	<–	Emotion intensity	0.520	**
Relationship strength	<–	Reciprocal exchange	0.262	**
Network position	<–	Network size	0.203	***
Network position	<–	Network density	0.218	**
Network position	<–	Centrality	0.173	0.09
Technological innovation	<–	Promotions	0.628	***
Technological innovation	<–	Relationship strength	0.220	***
Technological innovation	<–	Network position	0.232	***

Note: ***P < 0.001, **P < 0.01.

5.3. Structural equation modeling

SEM is a statistical technique that can effectively analyze complex multivariable data, and be used to construct, predict and validate causality. Popular programs used for SEM analysis include Lisrel, Amos, Eqs and Calis. Amos is used here to analyze the sample data and conduct the model fitting process.

First, path analysis is used to explore the causality between variables, i.e., the direct or indirect impacts of the independent variables on the dependent variable. Second, model parameter estimation and significance testing is carried out to ascertain the acceptability of the standardized coefficients. Third, the degree of adaptation is tested to judge the consistency between the model and practice. Several parameter estimation methods are available in Amos, with frequently used anti-discriminant diagnostics including: the standard error is too large; the error variance is lower than zero; and the standardized coefficient is higher than 0.95. Significance tests denote the direct relationships between variables, with a higher significance denoting better goodness of fit.

Based on the results of the goodness of fit analysis, the SEM is re-estimated through chi-square statistics. The Modified Index (MI) is used to predict the reduction in chi-square values, and the maximum parameter of MI is removed and combined with the chi-square fitting indicator to evaluate the model test results. The fixed coefficient or equivalent constraint is then modified to a free coefficient and Amos is operated again to analyze the results. Four such repetitions are usually needed for convergence to the solution.

The initial model path after fitting and modification is shown in Fig. 2, while the model parameter estimation results are shown in Table 4. The effect of the relationships between variables in Table 4 can be estimated by the standardized regression coefficients, whose values are the path coefficients shown above the arrows between the independent and dependent variables. Here, we take 0.01 as the discriminant value of the significance level of the standardized regression coefficients, with "**" indicating that the relationship effect between two variables is significant. Otherwise, the relationship effect is not significant. The results indicate that, with the exception of centrality and network position, all the relationship effects between variables are significant. The regression coefficients denote the direct strength of effect between two variables. Positive regression coefficients indicate a positive correlation between variables and negative otherwise.

As shown in Table 5, the values of the fitting indices for the SEM analysis meet the assessment standard for goodness-of-fit.

The overall fit of the model is good, and provides an intuitively acceptable representation of the relationships between the variables. The path coefficients are shown in Fig. 3.

5.4. Hypotheses test results

The goodness of fit and significance level of the variables can be used to evaluate the hypotheses. The standardized path coefficients in the relationship model denote the direct functional relationships between variables. The value of the coefficients range from 0 to 1, where closer to 1 denotes better functional performance. With the exception of H6, the significance level of all the hypotheses is less than 0.01, and so none except H6 are rejected (Table 6).

Table 5
Summary of the model fitting indices results.

Fitness index	Value	Assessment result
CMIN/DF	2.005	goodness of fitting
RMR	0.064	acceptable
RMSEA	0.074	goodness of fitting
IFI	0.871	acceptable
CFI	0.820	acceptable
NFI	0.772	acceptable
AGFI	0.906	goodness of fitting
PGFI	0.631	goodness of fitting

Note: CMIN/DF = Chi-square degrees of freedom; RMR = Root-mean square residual; RMSEA = root mean square error of approximation; IFI = incremental fit index; CFI = comparative fit index; NFI = normed fit index; AGFI = adjusted goodness-of-fit; and PGFI = parsimony goodness-of-fit index.

5.5. Discussion

In this study, it is hypothesized that the ICT innovation is significantly affected by relationship strength, network position and promotion by ICT innovation organizations. We also hypothesized that the relationship strength of ICT innovation organizations is significantly affected by interaction frequency, emotional intensity and reciprocal exchange, and the network position of ICT innovation organizations s significantly affected by network size, density and centrality. According the hypotheses test results in Table 5, the relationship strength of ICT innovation organization is significantly affected by interaction frequency, emotion intensity and reciprocal exchange. The network position of ICT innovation organizations is significantly affected by network size and density, which means that network centrality cannot significantly affect the network position of ICT innovation organizations. ICT innovation is significantly affected by relationship strength, network position and promotions of ICT innovation organizations.

The path coefficients reflect the level of variable impact on ICT innovation. The path coefficients are 0.63, 0.56 and 0.78 following a sequence of relationship strength, network position and promotion to ICT innovation. According the path coefficients, different strategies should be adopted in the process of ICT innovation. Promotion by ICT innovation organizations has the most positive impact on ICT innovation compared with relationship strength and network position, indicating the need to increase the strength of the relationship between different ICT innovation organizations in order to prompt ICT innovation development. The potential

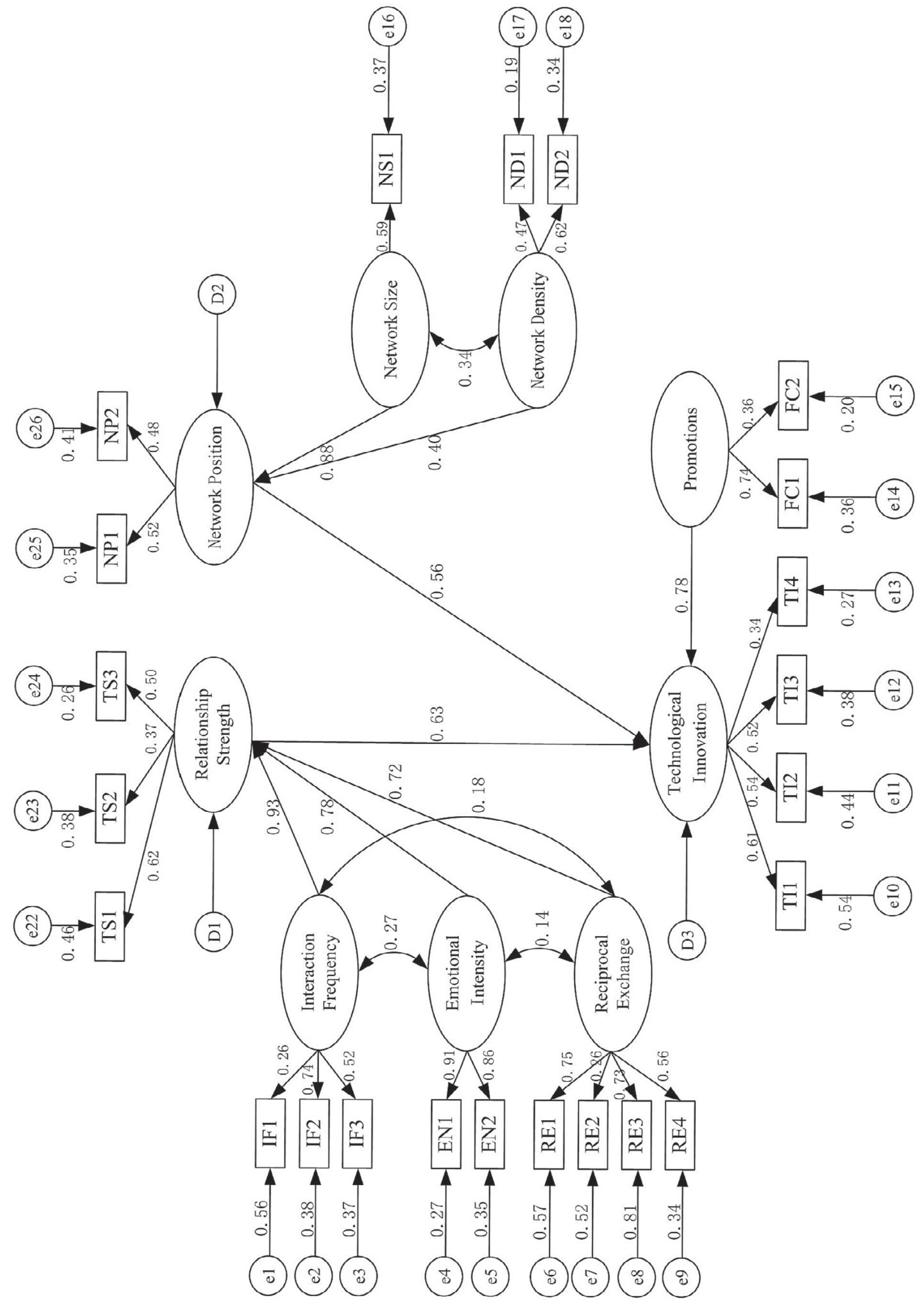

Fig. 3. Collaborative ICT innovation relationship path map (SEM analysis**).**

evolutionary paths towards ICT innovation are discussed in the following section from the perspective of relationship strength, network position and promotion of ICT innovation organizations.

That interaction frequency is significantly positively related with relationship strength is consistent with SNA theory, which holds that the more times two stakeholders cooperate and communicate in per unit time, the stronger will be their social ties. Stakeholders generate high interaction frequency because they communicate and cooperate, which enhances their relationship strength. The relationship between the interaction frequency and relationship strength of stakeholders in small-sized enterprises is stronger than that for large-scale corporations. Also, the smaller is the enterprise size, the stronger are the ties among the stakeholders. Due to their small business scope and simple organization structure, small-sized corporations have more opportunities to communicate and cooperate with each other, which can guarantee good interactions.

The relationship between interaction frequency and relationship strength is also relatively strong in non-state-owned enterprises. Non-state-owned corporations are more efficient and have a more open external environment, and therefore they have a more positive relationship between interaction frequency and relationship strength.

That emotional intensity is positively related to relationship strength coincides well with SNA theory, which holds that the deeper the emotional foundation, the stronger is the social tie. Close emotional connections can enhance trust between stakeholders, contribute to a deep cooperation and make their

Table 6
Results of hypothesis tests.

Hypothesis	Test result
H1:Interaction frequency significantly affects relationship strength.	True
H1a:Interaction frequency significantly affects relationship strength, and the smaller the enterprise size is, the more significant the relationship between stakeholders is.	True
H1b:Interaction significantly affects relationship strength, and it is more significant between non-state-owned stakeholders.	True
H1c:Interaction significantly affects relationship strength and it is more significant between stakeholders who are less experienced.	True
H2:Emotion intensity significantly affects relationship strength.	True
H3:Reciprocal exchange significantly affects relationship strength.	True
H3a:Reciprocal exchange significantly affects relationship strength. The larger the enterprise scale is, the more significant the relationship between stakeholders is.	True
H3b:Reciprocal exchange significantly affects relationship strength and it is more significant between stakeholders who are less experienced.	True
H4:Network size significantly affects network position.	True
H5:Network density significantly affects network position.	True
H5a:Network density significantly affects network position. The larger the enterprise scale is, the more significant the relationship between stakeholders is.	True
H5b:Network density significantly affects network position, and it is more significant between state-owned stakeholders.	True
H6:Centrality significantly affects network position.	Not valid
H6a:Centrality significantly affects network position, and the smaller the enterprise size is, the more significant the relationship between stakeholders is.	Not valid
H6b:Centrality significantly affects network position, and it is more significant between state-owned stakeholders.	Not valid
H6c:Centrality significantly affects network position, and it is more significant between experienced stakeholders.	Not valid
H7:Relationship strength significantly affects technological innovation.	True
H7a:Relationship strength significantly affects technological innovation and it is more significant between non-state-owned stakeholders.	True
H7b:Relationship strength significantly affects technological innovation, and it is more significant between experienced stakeholders.	True
H8:Network position significantly affects technological innovation.	True
H9:Promotions significantly affects technological innovation.	True

collaboration more efficient. Profound emotional intensity should bring about good business relations and a more favorable social network environment for collaborative innovation. By constantly strengthening emotional connections, the stakeholders of collaborative ICT innovation can form good and stable cooperative relationships with their business partners and willingness for long-term cooperation to improve the relationship strength in the whole network.

Because of the Chinese traditional social cultural background and the special nature of ICT innovators, reciprocal exchange plays a vital role in innovation networks stakeholder interactions. That reciprocal exchange is positively related to relationship strength is therefore unsurprising. During the process of ICT collaborative innovation, stakeholders use reciprocal exchange to supplement the internal resources involved and share new resources and technologies to create advantages for collaborative innovation. Stakeholders sharing information and resources for the purpose of reciprocal exchange more frequently and therefore have stronger ties.

In the process of ICT collaborative innovation, reciprocal exchange affects relationship strength more significantly for medium and large-sized enterprises. Medium and large-sized corporations have access to a wider external environment, and the diversity and heterogeneity of their external resources can better promote reciprocal exchanges to supplement the shortage of internal resources. Reciprocal exchange has a more significant impact on relationship strength for less experienced stakeholders. Experience plays an important role in the development and application of new technologies, affects the cooperation effects of work division in the innovation process and further influences collaborative innovation.

Network size is positively related to network position, where network size refers to the number of stakeholders comprising the collaborative ICT innovation network. The network evolves over time and has a constantly spreading boundary. This creates more opportunities for resource suppliers, diversifying the network resources of stakeholders. Therefore, the larger and more diverse is the network, the more likely it is to experience innovative scale and cluster effects.

Network density is positively related to network position. Larger enterprises have stronger ties, especially for the stakeholders of state-owned-enterprises. In general, the structure of network relationships is loose or tight, rather than evenly distributed. In regions where the network is loose, the relationships among building corporations, universities, research institutions, intermediary organizations and financial institutions are less close, negating the advantages of network position. Stakeholders obtain more resources and benefits, and better control information flow and resource sharing, by holding a favorable network position.

Centrality refers to the stakeholders' ability to control information and technologies, and previous studies suggest that this should affect network position. However, this conclusion is not supported here. This may be due to the particular background of industrialized building and the influence of the characteristics of collaborative ICT innovation. It is clearly an issue deserving further research.

Relationship strength is positively related to technological innovation and is more significant for the stakeholders (especially experienced stakeholders) of non-state-owned enterprises. Previous research indicates that strong ties theory is consistent with collaborative ICT innovation. Strong ties can be viewed as strong relationship strength. With a trusting, cooperative and stable innovative network, it is easier to transfer information and share resources. Moreover, strong ties are beneficial for collaborative ICT innovation stakeholders in coping with network environment change, uncertain shocks and crises.

Network position is positively related to technological innovation. Compared with other enterprises, those occupying the central network position are more likely to access new information from the network, which is beneficial to ICT innovation. Structural holes are special and significant network positions, as the information chain breaks once they disappear. Stakeholders holding structural holes have information and control advantages. Network position, therefore, significantly affects technological innovation by influencing stakeholder control of information and knowledge.

Promotion is significantly related to technological innovation. Important aspects of these are promotion policies, which include direct government R&D investment in industrialized construction and encouraging/protective policies. Support for promotion comes

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from the state, the whole industry, other relevant industries and internal or external practitioners. Promotion also needs to effectively break technology bottlenecks, reduce cost pressures, share interests and avoid risk factors by the means of collaboration.

6. Conclusions

This paper presents a combined method of SNA and SEM, and applies it to collaborative ICT innovation. A set of SNA-based hypotheses are proposed concerning the relationships between collaborative innovation, interaction frequency, emotional intensity, reciprocal exchange, network size, network density, centrality, relationship strength, network position, promotion, enterprise scale, nature and experience. An empirical study is carried out in the context of ICT innovation in prefabricated housing construction in China. Questionnaire data is used to fit and test an empirical causal model. The main results of the work are:

(1) A collaborative ICT innovation relationship model in which the strengths of the interaction paths between stakeholders are obtained and most of the SNA-based *a priori* hypotheses are well supported. SNA is therefore confirmed as providing a suitable conceptual basis for ICT innovation relationship modeling and analysis.
(2) This allows suggestions for enhancing collaborative ICT innovation capacity to be advanced to promote the interaction between stakeholders and the occupation of strategic positions.

In developing the SEM to show the strength of relationships between and within the SNA-based key factors and their influence on collaborative innovation, this builds on Shapira and Yehiel (2011) proposed innovative platform for collaboration between industry and academia; Xue et al. (2014) conceptual framework for construction innovation that emphasizes the critical role of collaboration; and Park et al. (2004) proposed construction dynamic innovation model based on system dynamics with multiple individual and situational impact factors, emphasizing the correlation between two key factors that drive construction innovation.

The study provides the basis for more detailed work, such as research into collaborative innovation activities within a particular range from a specific stage of industrialized building; the impact of a stakeholder behavior; and the development of a simulation system of collaborative ICT innovation relationships to better understand the synergistic aspects of the innovation processes involved. The SEM model and SNA method presented in this paper provide a new way to measure the relationships among stakeholders in ICT innovation, which are tested and analyzed in the context of ICT innovation in the prefabricated housing construction sector in China. Other applications are also possible, such as knowledge sharing in construction teams (Zhang and Ng, 2013), BIM technology applications in the construction industry (Lowry and Gaskin, 2014) and the organizational environmental of construction companies (Neppach et al., 2017). Future research is needed to continue in-depth from following three perspectives: (1) collaborative innovation activities studied within a specific range and starting from a specific segment of industrialized construction; (2) studying how a particular stakeholder innovation behavior influences collaborative innovation in industrialized construction processes; (3) the development of a simulation system that can simulate the collaborative relationships of industrialized construction in the innovation process.

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