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Schedule risks in prefabrication housing production in Hong Kong: a social network analysis

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Abstract

Various schedule risks beset prefabrication housing production (PHP) in Hong Kong throughout the prefabrication supply chain, from design, manufacturing, logistics, to on-site assembly. Previous research on the risks in prefabrication construction projects has mainly focused on the construction stage and has been confined to issues of completeness and accuracy without consideration of stakeholder-related risks and their cause-and-effect relationships. However, in reality, the supply chain is inseparable as precast components should be manufactured and transported to sites to fit in with the schedule of on-site assembly in seamless connection manner, and most risks are interrelated and associated with various stakeholders. This study applies social network analysis (SNA) to recognize and investigate the underlying network of stakeholder-associated risk factors in prefabrication housing construction projects. Critical risks and relationships that have important roles in structuring the entire network of PHP are identified and analyzed. BIM (Building Information Modelling)-centered strategies are proposed to facilitate stakeholder communication and mitigate critical schedule risks and interactions underlying the risk network. This study not only provides an effective method to analyze stakeholder-associated risk factors and to evaluate the effect of these risk factors from a network perspective, but also offers a new visual perspective in the promotion of the use of the Internet of things (IoT) and helps identify housing construction problems in Hong Kong.

Keywords: social network analysis, schedule risk, building information modelling, prefabrication housing production

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1. Introduction

The balance of housing supply and demand is a crucial concern in Hong Kong, which is one of the most densely populous areas in the world. Hong Kong has an area of 1,104 sq. km. and an average population density of 6,524 persons per sq.km according to the Hong Kong Annual Digest of Statistics 2015 (Census and Statistics Department, 2015). The limited availability of land and expensive land prices have resulted in the prevalence of high-rise building construction in Hong Kong. Only a small percentage of the population can afford the high prices of private housing, with about 50% of the population residing in public housing. More than 100,000 applicants are listed in the Housing Authority, awaiting public rental housing (PRH), possibly for at least seven years before moving into a rental place, given the PRH demand and supply (Chua et al., 2010). Housing issues in Hong Kong have resulted in widespread discontent. In addition, a series of problems and constraints have arisen in the construction industry of Hong Kong, including safety, labor shortage, time, and environmental protection. As a solution to housing problems, prefabrication construction is envisioned to gain momentum in Hong Kong against this socio-economic background, as in the face of the constraints in delivering the housing plan, prefabrication has been increasingly advocated owing to its potential benefits such as faster process, cleaner and safer working environment, and better quality (Tam et al., 2015; Uttam and Le Lann Roos, 2015).

However, other problems beset the industry of prefabrication housing construction. The processes of design, manufacturing, storage, transportation, and on-site assembly are fundamentally fragmented, nurturing a variety of risks that impose major pressure on the time management of prefabrication housing production (PHP). As a result, delay frequently occurs

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in PHP despite the promise of the government to meet the high housing demand. To help address these problems encountered in the construction of prefabrication housing, many studies have investigated the risk-related issues in the management of PHP. However, these studies do not consider risks from the perspective of stakeholders, despite these risks being subject to different stakeholders designated to perform different tasks under different construction scenarios. Previous studies also do not sufficiently consider the interrelationships underlying the risk factors and their actual influence on a network basis. Thus, this research proposes a model to evaluate the stakeholder-related risks found in four major prefabrication construction processes, employing the social network analysis (SNA) method. Critical risks and interactions that significantly influence the time management of PHP are identified, and corresponding BIM-centered strategies are proposed to address the challenges encountered in the time management of PHP.

2. Background research

2.1 PHP in Hong Kong

Also called off-site construction, prefabrication construction refers to structures built at a location other than the location of use (Gibb, 1999). The construction of structural parts occurs in a manufacturing plant specifically designed for this type of process, which is typically contrasted to traditional on-site housing production. PHP processes in Hong Kong are summarized in Figure 1: (a) design, (b) manufacture, (c) cross-border logistics, and (d) on-site assembly. Normally, a client, which is normally Hong Kong Housing Authority in Hong Kong, hires designers for architectural and engineering design, with special consideration given to the adoption of modules and their structural safety, buildability, and transportation convenience.

The design information is then transmitted to the manufacturer for the production of precast components. The whole prefabrication manufacturer sector of Hong Kong has been moved to offshore locations in the PRD (Pearl River Delta) region in China, such as Shenzhen, Dongguan, Huizhou, Zhongshan, and Shunde. After the precast elements are produced at the PRD, companies with better coordination can transport the components through Shenzhen–Hong Kong customs and directly reaching construction sites in Hong Kong. Others most of companies have to store their components in a temporary storage in Lok Ma Chau, which is a large area close to the customs facility, for conveyance buffer purpose. Lastly, these precast components are installed by the assembly company to replace the traditional cast in-situ work. Unlike the processes in conventional cast in-situ construction, prefabrication housing is considered to be a significant process innovation that can greatly facilitate housing production as it allows: (1) compressed project schedules that result from changing the sequencing of work flow (e.g., allowing for the assembly of components offsite while foundations are being poured on-site; allowing for the assembly of components offsite while permits are being processed) (Tam et al., 2007); (2) more controlled conditions for weather, quality control, improved supervision of labor, easier access to tools, and fewer material deliveries (Mao et al., 2015; Ingrao et al., 2014a; Ingrao et al., 2014b); (3) fewer job-site environmental impacts because of reductions in material waste, air and water pollution, dust and noise, and overall energy costs (Tam et al., 2005; Li et al., 2015; Tam and Hao, 2014; Tam et al., 2014; Hong et al., 2016), and (4) reduced requirements for on-site materials storage, and fewer losses or misplacement of materials (Li et al., 2014a; Li et al., 2014b; Wang et al., 2015)

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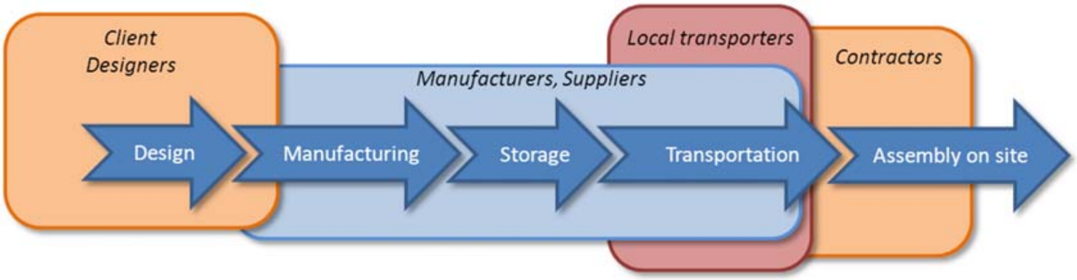

Figure 1. Prefabrication housing processes

2.2 Stakeholders and schedule risks in PHP

In recent year, the view of PHP project success has transformed from achieving the specific indicators such as safety, cost, quality and time towards a human-based perspective of achieving stakeholder satisfaction. Nevertheless, stakeholders have different interests in and therefore sometime might have negative effects on a system (Borgatti et al., 2009). For example, based on their information needs, different stakeholders in PHP have over the past few years developed their own enterprise information systems (EISs). Though the information captured in these systems may have greatly facilitated the operations undertaken by different stakeholders, these heterogeneous systems cannot talk to each other owing to many reasons such as different databases, functions, and operating systems. Another example is the adversarial culture in PHP industry. The stakeholders in housing production may include clients (e.g., private developers and public developers such as Hong Kong Housing Authority), designers, consultants, contractors, suppliers, sub-contractors, end users, and facility managers. Various stakeholders involved in PHP have a hub-and-spoke representation, where the project occupies a central position and has direct connections with the related stakeholders. So the key

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stakeholders, such as designers and contractors, are not necessarily involved in the whole project life cycle, witnessing the discontinuity of different parties and different stakeholders that are designated to perform different tasks throughout the main processes of design, manufacturing, storage, transportation, and assembly on site. As such, they are not be able to work together and communicate with each other efficiently and, in fact, can have competing interests. This problem is often referred to as the fragmentation and discontinuity that exists in the supply chain of PHP, which can be further exacerbated by the fact that the whole prefabrication manufacture sector has been moved to offshore areas in the PRD region (new stakeholders, such as the offshore manufacturers, transporters, and host local authorities, are involved, resulting a more complex organization structure) for a reason of lower material and labour cost. With the fragmentation and discontinuity problems, various stakeholder-associated risks, such as low information interoperability between different enterprise resource planning systems, inefficient design data transition and weak response to design change during construction, are nurturing throughout the supply chain of PHP, causing frequent schedule delay that beset the prefabrication industry in Hong Kong.

Under the current design, bid, and build (DBB) used as the typical housing delivery model, the construction of the project has been awarded to the main contractor, and the main contractor will serve as the manager for the overall project, such that every single task of sub-contractor will under the management of the main contractor. As such, main contractors have to guarantee that design information and orders of prefabrication components should be passed from designers to client, to main contractor and finally reach to prefabrication plants without any ambiguity to ensure effective manufacturing, and components should be manufactured and transported to sites to fit the work crew’s schedule. Among these complex and fragmented processes, various schedule risks, particularly information-related risks, emerge. For instance, stakeholders are basically self-guarded interest centers from different companies; sharing information amongst them is not the industry-wide culture. This might generates "information islands", which can be considered as bodies of information that needs to be shared but has no network connection. Information islands lead to a variety of schedule risks, such as design information gap between designer and manufacturer, logistics information inconsistency. These schedule risks might serve as trigger that generate new type risks or expand the impact to existing risks, resulting in frequent delay in PHP. An integrated information platform contributed and shared by various stakeholders from different companies might be the key for alleviating the "information islands" problem, improving information interoperability among different enterprise resource planning systems, raising the level of design data transition efficiency, and enhancing communication among various stakeholders. Given the discussion above, how to identify critical schedule risks and corresponding stakeholders, and quantify their impact from a network perspective has been a major concern for solving schedule delay problems in the prefabrication housing industry. To deal with the concern, this study analyzes stakeholder-associated risks in PHP through social network theory, such that the corresponding BIM-centered strategies can be formulated to address those practical problems.

3. Methodology

3.1 Research flow of SNA

Social network theory views the supply chain of PHP as a complex system containing various stakeholders and relationships. The purpose of network analysis is to analyze stakeholder-associated schedule risks in PHP and their cause-and-effect relationships. This methodology

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has been applied in various research areas, including but not limited to green building project (Yang and Zou, 2014), waste management (Caniato et al., 2014), construction industry (Zou et al., 2006), information science (Otte and Rousseau, 2002), and social science (Borgatti et al., 2009). Nevertheless, the use of SNA for risk analysis in the research field of prefabrication construction appears to be an uncovered area. The general process of SNA can be divided into four main parts: (1) identification of stakeholders and their schedule risks, (2) determination of risk interrelations, (3) determination of the risk network, and (4) identification and verification of risk mitigation strategies.

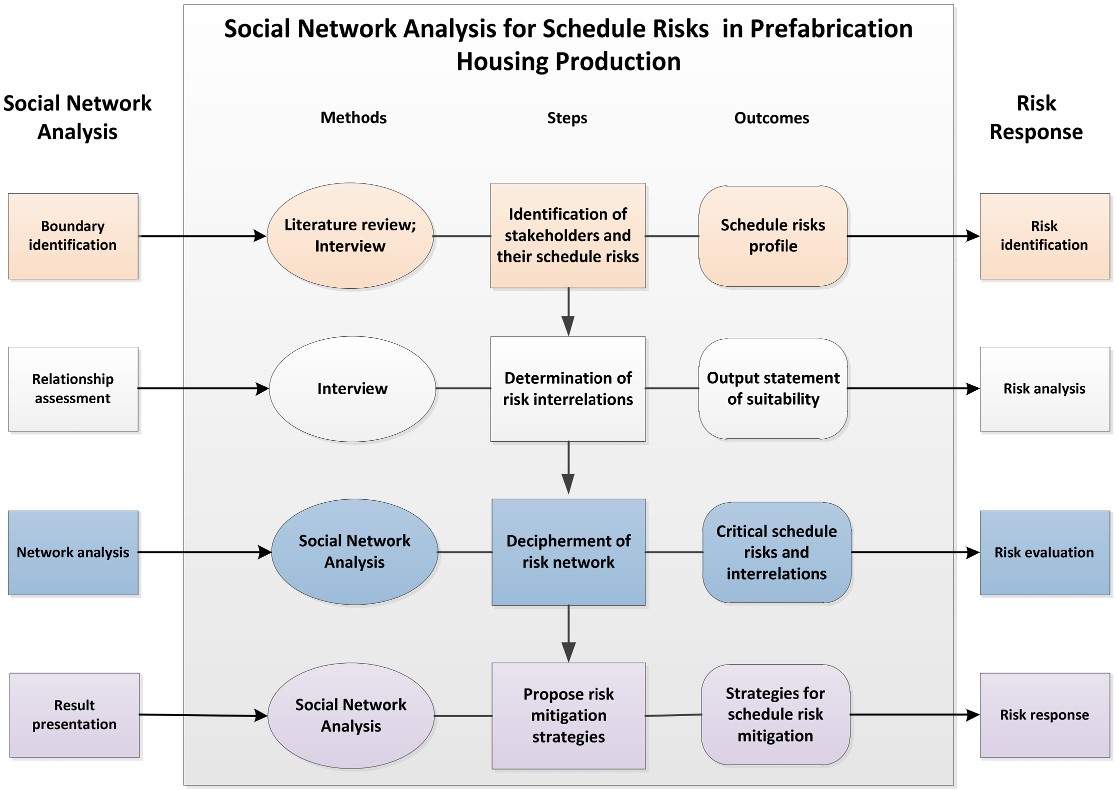

Figure 2. Research flow

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Figure 2 shows the network development process in this study. The first step identifies the stakeholders and schedule risk factors that directly influence the PHP. Chain referral sampling is applied for this purpose (Biernacki and Waldorf, 1981), that is, to completely identify stakeholders and their associated risks. Two representatives from the main contractor and manufacturer were approached to initiate the chain. They were asked to locate closely-related stakeholder groups. These referrals were then asked to locate any potentially affecting or affected stakeholder groups who were not yet included in the chain. A tentative stakeholder list previously compiled based on the document analysis of previous literature was provided as reference in the referral process. Along with stakeholder identification, the stakeholder-related schedule risks of PHP were identified through a series of semi-structured interviews. The interviews were conducted with representatives from seven stakeholder groups. The participants all had direct involvement in the supply chain of PHP, and to ensure the representativeness and reliability of the collected data, the chosen participants were at or above the senior managerial level and had at least five years of experience in their expertise. Based on their empirical knowledge, the respondents were invited to express their views on the following three main questions: (1) What are the major risks that may influence the schedule of PHP? (2) To what extent can these risks lead to schedule delay? (3) How do these identified risks relate to the corresponding stakeholders? A reference list of stakeholder risks previously compiled based on document analysis and literature review was provided to facilitate the process. The interviews were transcribed, and the manuscripts were returned to the participants for feedback.

The second step determines the interrelations between the identified schedule risk factors. In this study, links are defined as the influence of stakeholder-related risk over another risk. For this purpose, a survey was designed to elicit responses from the representatives of the identified stakeholder groups. At the outset, the researchers provided verbal explanations/instructions (by telephone or face-to-face) for the survey structure and questions to the participants to minimize ambiguities in completing the survey. The survey questions required the participants to consider all possible interrelationships between various schedule risk factors based on their empirical knowledge. The respondents were asked to clearly define the direction of potential influence because the relationships can be reciprocal. For example, the influence exerted by S_aC_b on S_cC_d was distinguished from the influence of S_cC_d on S_aC_b, and they were treated as two different links. After listing the identified links, the respondents were asked to quantify each link in two aspects: the *intensity of influence* given by a concern over another and the *likeliness* of the occurrence of this influence, using a five-point scale where “1” and “5” denote the lowest and highest levels, respectively. The multiplication of the intensity of influence and likeliness provides a basis for assessing the influence level between two stakeholder-associated risks. When no influence exists between two nodes, the influence level is zero.

In the third step, the adjacency matrix, together with the node and link lists, was imported into NetMiner 4 as the major input data for network visualization and analysis. The step started with a visual inspection to gain initial insights into the main risk factors and their distribution in the influence network, and this sub-step was followed by a descriptive investigation based on network density and cohesion. These two metrics were chosen because they were good indicators of a network’s overall characteristics in terms of connectedness and complexity, reflecting the highly complicated relationships in the project. After descriptive analysis was performed, node-level metrics were calculated to explore the properties and roles of individual nodes and to determine the critical stakeholder-related risks. Along with node-level, link betweenness centrality was computed to measure the importance of interrelationships among risks. This investigation focused on relationships sourcing from or targeting the main stakeholder-associated risks identified in the node-level results to unlock the cause-and-effect relationships underlying these risk factors. The purpose was to recognize the main relationships in the network and to check any concern interactions with centrality scores greater than the cut-off point but not sourcing from or targeting the key nodes. Such links should be included as well to ensure the inclusiveness of the link-level analysis. The outcome of the network analysis was a list of critical stakeholder-related risks and the critical interactions underlying those risk factors.

The final stage involves understanding the actual meanings of the identified critical risk factors and interactions and categorizing these key relationships based on their meanings. In consolidating the SNA results with the interview findings previously collected before network analysis, these major stakeholder-related risks are further discussed. Corresponding strategies for mitigating the identified critical schedule risks and interactions are proposed and discussed to address real-world problems in PHP, and these strategies are validated through the established social network model.

3.2 Main metrics in SNA

In this study, six SNA indicators are computed to investigate the structural characteristics and patterns embedded in the stakeholder issue network at both the network and node/link levels.

Network density

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Density captures the overall connectivity of a network. It refers to the proportion of actual links presented within a network to the maximum number of potential links if all the network actors are interconnected with one another (Wasserman and Faust, 1994). The density value varies between zero (i.e., all nodes are isolated) and one (i.e., a complete network with all nodes tied to everyone else), depending on the network size. More interactions among stakeholder risks result in a greater network density.

Network cohesion

Cohesion indicates network complexity by considering the reachability of stakeholder risks, where reachability is defined as the number of links to approach nodes in a network according to the geodesic distance (Parise, 2007). A high cohesion value indicates a complicated stakeholder issue network, as more walks are required from each node to reach everyone else.

Nodal degree

Nodal degree reflects the extent to which a stakeholder issue is tied to its immediate neighbors in a network by measuring the weight sum of relations that are directly incident with the node (Wasserman and Faust, 1994). Nodal degree is further categorized into in-degree (i.e., incoming links received by the node) and out-degree (i.e., outgoing links emitted from the node) according to the direction of links. The degree difference is also calculated as 216 by subtracting the in-degree score from the out-degree score. A stakeholder issue with a large degree difference can be interpreted as exerting stronger influences on its neighbors than accepting influences. In considering node types, “isolated” nodes are relatively easy to handle, as these stakeholder risks are not linked to other nodes.

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Betweenness centrality

Betweenness centrality calculates the occurrence in which a specific node/link is situated between other pairs of nodes/links on the basis of the shortest path. This measure identifies nodes/links that have an intermediary role to connect different parts of a network, and "weaknesses at these critical points can lead to disintegration" (Pryke, 2012). A node/link with a high betweenness centrality score possesses great power in controlling the interactions or influences flowing through it.

Status centrality

Status centrality is a node measure that reflects the overall influence of a stakeholder issue on the entire network. This indicator calculates the number of a node's direct successors and predecessors and the secondary nodes that are linked indirectly to the focus node via its immediate neighbors (Katz, 1953). Status centrality is further classified into in-status centrality (impact received) and out-status centrality (impact released). Nodes with greater out-status centrality scores are worth more attention, as they are deemed to be more influential with a larger magnitude of influence.

Brokerage

Brokerage describes the role and capability of a particular node in bridging different subgroups within a network under a selected partition vector (Gould and Roberto, 1989). In this study, the subgroups/partitions in the stakeholder issue network are the various stakeholder or issue categories identified in the stakeholder issue schedule. After choosing a partition vector, this node measure counts the frequency of each of the five brokerage configurations (coordinator,

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representative, liaison, gatekeeper, and itinerant) that occur on every node. Nodes with high brokerage scores are worth more attention because they have critical roles in producing propagating effects and increasing the overall network complexity.

4 SNA-based risk analysis

4.1 Data collection results

After a series of interviews was conducted, a total of seven stakeholder groups directly involved in PHP were identified. They are coded numerically as S_a, where a = 1 to 7, namely, (1) client, (2) designer, (3) main contractor, (4) manufacturer, (5) logistics, (6) assembly company, and (7) local government. Along with the major stakeholders, a total of 35 stakeholder-associated schedule risks were also identified. The number of schedule risks and related stakeholders are summarized in Table 1. These nodes were coded numerically into S_aR_b for network data processing, in which a indicates a specific stakeholder group, and b represents the related schedule risk factor. Based on literature review and interviews, a total of 30 schedule risk factors are identified, with seven respective stakeholders groups generating 52 nodes. After the risk nodes are identified and coded, the links in the risk network representing the influence between two nodes are further defined and numbered. Links represent relations and dependencies among objects. Three basic types of relationships between each pair of risks exist in the organizational structure: (1) An independent relationship refers to risks that are not related to each other. (2) A dependent relationship indicates that a direct influence exists between two risks. (3) An interdependent relationship refers to risks that are in a mutually dependent relationship directly or within a large loop. The classical risk assessment approach is used to evaluate the consequence and likelihood of each risk on project objectives. In our study, risk relationship instead of individual risk is defined by the influence of one risk on the other and the likelihood of the interaction between the risks. From the survey responses, 597 links joining 52 nodes were defined in total. An adjacency matrix representing the influence network G (52,597) of stakeholder risks was created accordingly, in which the 52 nodes were found at the first row and column, and the influence levels of the 597 links were put into the corresponding cells.

Table 1. Identified schedule risks and associated stakeholders

Risk ID	S. Node	Stakeholders	R. Node	Risk name	Source	Category
S1R1	S1	Client	R1	Inadequate project funding	(Mojtahedi et al., 2010)	Cost
S3R1	S3	Main contractor				
S1R2	S1	Client	R2	Inefficiency of design approval	(Hossen et al., 2015)	Organizational
S1R3	S1	Client	R3	Low information interoperability between different enterprise resource planning systems	Interview	Information transfer
S2R3	S2	Designer				
S3R3	S3	Main contractor				
S1R4	S1	Client	R4	Change in project scope	(Taylan et al., 2014)	Cost
S2R4	S2	Designer				
S3R4	S3	Main contractor				
S4R4	S4	Manufacturer				
S5R4	S5					

S6R4	S6	Logistics				
		Assembly company				
S1R5	S1	Client	R5	Tight project schedule	(Taylan et al., 2014)	Organizational
S2R5	S2	Designer				
S3R5	S3	Main contractor				
S6R5	S6	Assembly company				
S2R6	S2	Designer	R6	Incomplete design drawing	(Mojtahedi et al., 2010)	Quality
S1R7	S1	Client	R7	Design change	(Hossen et al., 2015)	Quality
S2R7	S2	Designer				
S3R7	S3	Main contractor				
S3R8	S3	Main contractor	R8	Safety accident occurrence	Interview	Safety
S2R9	S2	Designer	R9	Redesign because of errors in design	(Hossen et al., 2015)	Quality
S2R10	S2	Designer	R10	Inefficient design data transition	Interview	Information transfer
S3R10	S3	Main contractor				
S3R11	S3	Main contractor	R11	Inefficient verification of precast components because of ambiguous labels	Interview	Information transfer

S3R12	S3	Main contractor	R12	Inefficient communication between project participants	(Taylan et al., 2014)	Information transfer
S3R13	S3	Main contractor	R13	Weak response to design change during construction	Interview	Organizational
S3R14	S3	Main contractor	R14	Inadequate planning and scheduling	(Hossen et al., 2015)	Organizational
S3R15	S3	Main contractor	R15	Delay of the delivery of precast elements to site	(Mojtahedi et al., 2010)	Organizational
S4R16	S4	Manufacturer	R16	Design information gap between designer and manufacturer	Interview	Information transfer
S4R17	S4	Manufacturer	R17	Serial number recording error	Interview	Information transfer
S4R18	S4	Manufacturer	R18	Precast components mistakenly delivered	(Aibinu and Odeyinka, 2006)	Organizational
S4R19	S4	Manufacturer	R19	Remanufacturing because of quality control and damage during production	Interview	Quality
S4R20	S4	Manufacturer	R20	Misplacement on the storage site because of carelessness	Interview	Information transfer
S5R21	S5	Logistics	R21	Transportation vehicle damage	Interview	Quality
S5R22	S5	Logistics	R22	Transportation road surface damage	(Hossen et al., 2015)	Environment

S5R23	S5	Logistics	R23	Reapplication of custom declaration	Interview	Safety
S5R24	S5	Logistics	R24	Logistics information inconsistency because of human errors	Interview	Information transfer
S5R25	S5	Logistics	R25	Custom check	Interview	Safety
S6R26	S6	Assembly Company	R26	Difficult identification of proper precast components	Interview	Information transfer
S6R27	S6	Assembly Company	R27	Slow quality inspection procedures	(Aibinu and Odeyinka, 2006)	Organizational
S6R28	S6	Assembly Company	R28	Tower crane breakdown and maintenance	Interview	Quality
S6R29	S6	Assembly Company	R29	Installation error of precast elements	Interview	Information transfer
S7R30	S7	Government	R30	Excessive approval procedures	(Taylan et al., 2014)	Organizational
S7R31	S7	Government	R31	Uncertain governmental policies	(Yang and Zou, 2014)	Environment
S7R32	S7	Government	R32	Imperfect technological specifications on prefabrication	(Yang and Zou, 2014)	Quality
S3R33 S6R33	S3 S6	Main contractor Assembly company	R33	Civil disturbances	(Aibinu and Odeyinka, 2006)	Environment
S3R34 S6R34	S3 S6	Main contractor	R34	Labor dispute and strikes	(Aibinu and	Environment

		Assembly company			Odeyinka, 2006)	
S3R35 S6R35	S3 S6	Main contractor Assembly company	R35	Inclement weather	(Hossen et al., 2015)	Environment

4.2 SNA analysis results

4.2.1 Network level results

Figure 3 captures the risk network composed of 52 stakeholder risks connected by 597 links. The node colors and shapes indicate the risk and stakeholder categories, respectively. An arrow illustrates the existence of an influence relationship between a pair of stakeholder-associated risks, and its thickness represents the influence level. Risks with more links occupy a more central position in the network, whereas risks with fewer connections are located closer to the network border.

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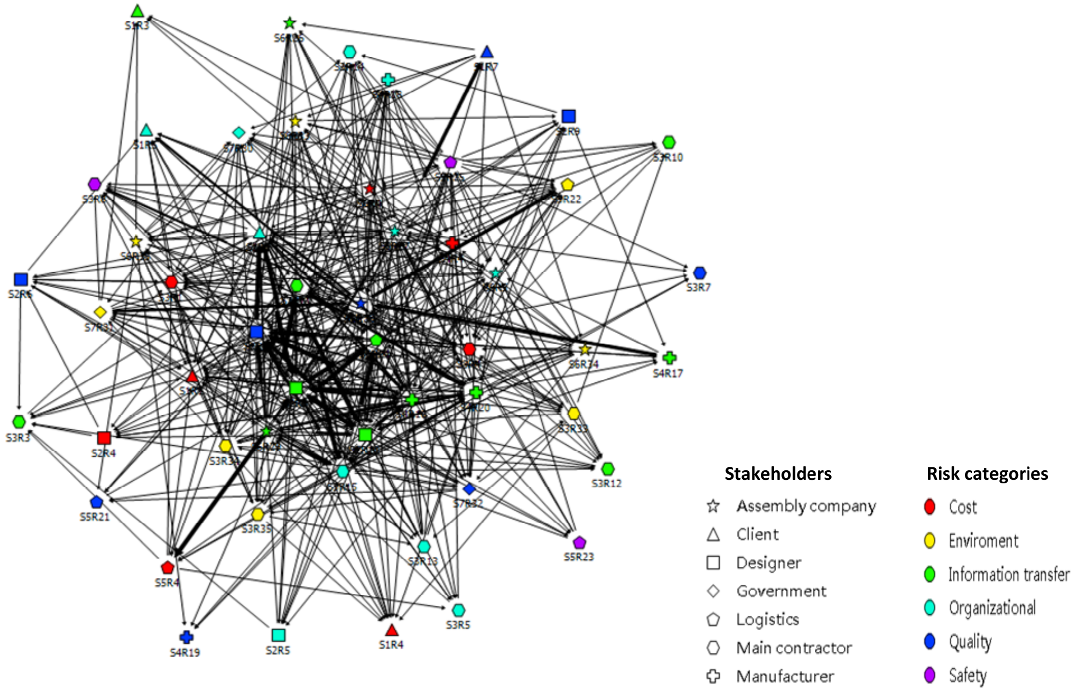

Figure 3. Stakeholder-associated schedule risk network

A visual inspection of the network map provides initial insights into the overall network structure. All risks are interconnected, implying great complexities in the stakeholder management process, in view of the numerous cause-and-effect relationships underlying various stakeholder risks. A large area of green nodes tend to be located in the center of the map, showing that the risks related to information transfer are closely interrelated, and their interactions account for the majority of existing links. The calculation of network level metrics provides a clear lens to investigate the network configuration quantitatively. The network density is 0.225, and the mean distance between nodes is 1.928 walks, indicating that the network is dense, and the risks are proximate to each other. The network cohesion is 0.962. A higher network cohesion for the density value implies that the structure is more intricate from the perspective of node approachability.

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4.2.2 Node and link level results

To identify important stakeholder risks, this part explores the direct and propagating impacts of individual nodes and their roles in the network. The status centrality map that depicts the relative outgoing impact of a stakeholder concern, including all risks, is shown in Figure 4. Some interesting findings are identified. The risks related to client, designer, main contractor, and manufacturer are located relatively centrally. This finding indicates the high influence of these stakeholders on the PHP process. Assembly company and logistics also have considerable roles in PHP. The information transfer and quality risks related to different stakeholder groups seem to be more significant than other risk categories. This finding is different from those of previous research, in which the cost-related risks are considered to be more important. The significance of information transfer-related risks in PHP highlights innovative Internet technology, which may increasingly have a more importation role in the construction industry. Along with status centrality, three other metrics, including out-degree, degree difference magnitude, and ego network size, are initially computed for the nodes, relatively measuring the direct out-going influence, net influence level, and extent of influence, respectively.

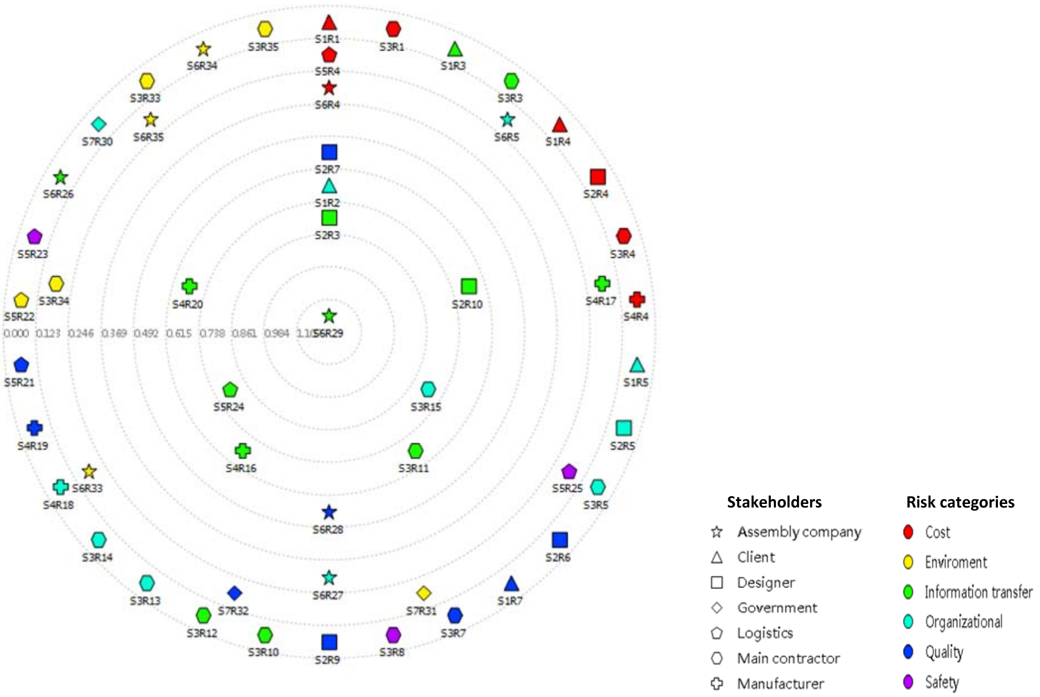

Figure 4. Status centrality map

Table 2 presents the twelve rankings in each of the out-status centrality, ego network size, out-degree, and degree difference magnitude results. As shown in Table 2, three stakeholder-associated risks ranked in accordance to ego size are identified: S6R28 (“crane breakdown and maintenance problem” sourced from the assembly company), S2R3 (“low information interoperability between different enterprise resource planning systems” sourced from the designer), and S5R24 (“logistics information inconsistency because of human errors” sourced from logistics). With regard to out-degree indicator, S1R2 (“inefficiency of design approval” sourced from the client), S2R3 (“low information interoperability between different enterprise resource planning systems” sourced from the designer), and S6R27 (“slow quality inspection procedures” sourced from the assembly company) are considered to be the three most significant risk factors. In terms of the metric of the degree difference, S5R25 (“low information interoperability between different enterprise resource planning systems" sourced from the designer), S6R4 ("change in project scope" sourced from the assembly company), and S1R2 ("inefficiency of design approval" sourced from the client) are regarded as factors that have significant net influence level. These critical risks are worth careful attention considering their great direct and/or propagating influences on many successors and/or predecessors.

Table 2. Top stakeholder-associated risks based on status centrality and ego network size nodal degree analyses

	Out-status Centrality		Ego Size		Out-Degree		Degree difference	
1	S6R29	1.230	S6R28	36	S1R2	27	S2R3	19
2	S3R15	0.853	S2R3	34	S2R3	27	S6R4	11
3	S2R3	0.834	S5R24	34	S6R27	26	S1R2	10
4	S5R24	0.819	S6R27	34	S2R7	25	S3R34	8
5	S3R11	0.730	S3R11	33	S4R16	25	S5R4	7
6	S4R16	0.720	S2R7	32	S2R10	24	S1R7	7
7	S4R20	0.720	S2R10	32	S4R20	24	S5R25	6
8	S2R10	0.714	S1R2	31	S3R15	23	S3R33	6
9	S1R2	0.656	S4R16	31	S5R24	23	S3R15	4
10	S2R7	0.585	S3R15	30	S5R25	23	S7R32	4
11	S6R28	0.557	S4R20	30	S6R28	23	S6R35	4
12	S6R27	0.261	S6R29	29	S3R11	22	S3R13	4

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Brokerage is a useful indicator in examining the functions and abilities of individual nodes in connecting subgroups. Table 3 shows the top ten ranking in the brokerage analysis under the partition vector of stakeholder entities. These nodes are also considered to be critical risks in this case because of their significance in bridging various stakeholder groups. The top three nodes are S6R27 ("slow quality inspection procedures" sourced from the assembly company), S6R28 ("crane breakdown and maintenance problem" sourced from the assembly company), and S2R7 ("design change" sourced from the designer), with values of 455, 401, and 375, respectively.

Table 3. Top stakeholder-associated risks based on brokerage analysis

		Coordinator	Gatekeeper	Representative	Itinerant	Liaison	Total
1	S6R27	23	96	74	47	215	455
2	S6R28	7	44	62	46	242	401
3	S2R7	7	36	50	55	228	376
4	S2R3	5	28	36	50	208	327
5	S5R24	0	17	30	51	222	320
6	S3R11	16	81	33	34	133	297
7	S4R20	3	19	25	44	204	295
8	S4R16	3	21	26	37	204	291
9	S2R10	5	31	29	43	176	284
10	S6R29	7	44	39	33	146	269
11	S3R15	7	70	20	27	135	259
12	S1R2	0	17	0	38	185	240

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Table 4 displays the top twelve stakeholder-associated risks and the interrelations with the highest betweenness centrality. Betweenness centrality reflects the extent to which a risk or interaction acts as a gatekeeper to control the influences flowing through it, that is, the power in controlling influence. A higher betweenness centrality score indicates a greater importance of the risks and interrelations. Among all the 597 links, 12 relationships are found as sourcing from or targeting the identified key risks, with a betweenness centrality value greater than 29.5. As shown in Table 4, these 12 links are recognized as the key interactions in PHP because they indicate the major causes and/or potential consequences of the important stakeholder risks. To understand the results, the top twelve nodes with the highest node betweenness are also listed in the table. These nodes are also considered critical because without them, the complex propagating influences on the stakeholder risk network are largely reduced.

Table 4. Key stakeholder-associated risks and interactions according to the betweenness centrality

Rank	Risk ID	Node betweenness centrality	Link ID	Link betweenness centrality
1	S2R3	0.126648	S2R3→S4R16	51.5
2	S6R29	0.080381	S2R10→S6R29	51.2
3	S2R7	0.068639	S4R16→S5R24	51.1
4	S6R27	0.060862	S4R16→S2R7	38.5
5	S3R15	0.053522	S2R3→S6R27	36.4
6	S5R24	0.049473	S2R3→S3R15	34.8
7	S4R20	0.047281	S4R16→S6R29	34.6

8	S2R10	0.045992	S5R24→S3R15	32.4
9	S6R28	0.040858	S2R7→S1R2	32.1
10	S4R16	0.040789	S6R28→S3R15	29.5
11	S3R11	0.040654	S2R3→S4R20	28.3
12	S6R5	0.033829	S2R7→S1R2	28.1

5 Major challenges and BIM-centered strategies in PHP

5.1 Identification of critical risks and challenges

The identification process relies on the results of SNA indicators in the above section, including degree of nodes, betweenness centrality, status centrality, and brokerage. In short, the risk interrelationships with higher output degree, higher degree difference, higher betweenness centrality, higher status centrality, and higher brokerage values should be identified with more attention. In consolidating the results of SNA indicators, a list of 12 critical stakeholder risks and relationships sourced from or targeted to these nodes is generated, as shown in Table 5. The next step is to comprehend the actual meanings of these critical risks and links to ultimately identify the major challenges faced by stakeholders in PHP under intricate concern interactions. This step can be accomplished by categorizing the critical risks and interactions based on their actual meanings, as presented in Table 5.

Table 5. Critical stakeholder risks and interactions

Challenges in PHP	Critical risks	Risk description	Associated stakeholder	Associated critical links

Production Information sharing barriers between Prefabrication manufacturer and logistics and assembly companies that lead to extra negotiation time	S5R24	Logistics information inconsistency because of human errors	Logistics	S2R3-S3R15
	S2R3	Low information interoperability between different enterprise resource planning systems	Designer	S2R3-S4R16
Lack of Just-In-Time (JIT) delivery and assembly in compact site area	S3R15	Delay of the delivery of precast element to site	Main contractor	S5R24-S3R15
	S6R29	Installation error of precast elements	Assembly company	S4R16-S6R29
Difficulty for embedding the design information in the prefabrication components for further use	S2R7	Design change	Designer	S2R7-S1R2
	S6R27	Slow quality inspection procedures	Assembly company	S2R3-S6R27
Communication barriers among stakeholders and managers	S6R28	Tower crane breakdown and maintenance	Assembly company	S6R28-S3R15
	S1R2	Inefficiency of design approval	Client	S2R7-S1R2
Inefficiency in passing the design information to the manufacturers without any ambiguity	S2R10	Inefficient design data transition	Designer	S2R10-S6R29
	S4R16	Design information gap between designer and manufacturer	Manufacturer	S4R16-S2R7
Difficulties in the identification and	S3R11	Inefficient verification of precast components	Main contractor	S4R16-S5R24

verification of proper precast components		because of ambiguous labels		
	S4R20	Misplacement on the storage site because of carelessness	Manufacturer	S2R3-S4R20

Two relationships (including "S2R3-S3R15" and "S2R3-S4R16") describe risks about information inconsistency among different enterprise systems, which may delay the delivery of precast elements to the site in the process of PHP, whereas the two critical risks "S5R24" and "S2R3" also shed light on the logistics information inconsistency and low information interoperability. Consequently, they are put under the same category, and one major stakeholder challenge is determined: "production information sharing barriers between prefabrication manufacturer and logistics and assembly companies that lead to extra negotiation time." Following the same principle, five major challenges encountered by stakeholders in the project are identified: (1) adopting highly complex and leading-edge technology, (2) lack of just-in-time (JIT) delivery and assembly in compact site area, (3) communication barriers among stakeholders and managers, (4) inefficiency in passing the design information to the manufacturers without any ambiguity, and (5) difficulties in the identification and verification of proper precast components. In the next section, these five challenges are further investigated, and the corresponding strategies are developed according to the SNA results to handle the identified challenges and mitigate critical risks and interactions.

5.2 BIM-centered strategies for PHP

The introduced SNA indicators provide useful information to help project teams understand the direct risks and propagated interactions, whereas this section mainly focuses on proposing effective risk mitigation strategies to handle the critical risks and interactions obtained in the previous section. These strategies are proposed in an attempt to achieve the following three fundamental goals: (1) to resolve critical risks, (2) mitigate critical risk interactions, and (3) enhance communication among critical stakeholders. With these goals, an RFID-enabled building information modeling platform (RBIMP) is proposed in this study to resolve risks, mitigate interactions, and enhance communication among stakeholders in the PHP.

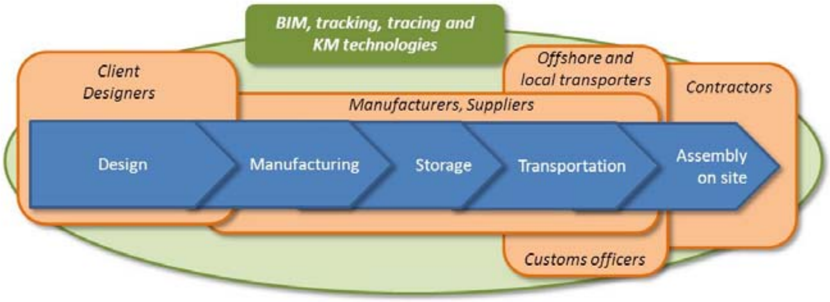

Figure 5. Prototype of the proposed RBIMP for offshore PHP

The key components of the architectural structure of the proposed RBIMP are categorized into three dimensions—platform as a service (PaaS), infrastructure as a service (IaaS), and software as a service (SaaS)—which are the major modules designed for handling information transfer-related risks factors and facilitating major stakeholders involved in a PHP system. RBIMP uses the service-oriented open architecture as a key innovation to enable the PaaS. Given its potential to manage building information throughout the whole project lifecycle, PaaS is considered to be the backbone of the platform, aiming to reengineer the offshore PHP in Hong Kong. As shown in Figure 6, the prototype of the platform considers the production processes, stakeholders, information transfer flow, and real-time information visibility and traceability. Four detailed strategies are proposed for the development of RBIMP, as shown in the Figure

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6: (1) map the offshore prefabrication processes in the HK–PRD setting, (2) capture the information flow throughout the offshore prefabrication construction processes, (3) improve the information interoperability and real-time information visibility and traceability of the offshore prefabrication construction using auto-ID technologies, and (4) integrate people, offshore prefabrication processes, information flow, and technologies in a BIM-centered system. These four strategies together serve as a whole for the development of the proposed RBIMP to help deal with the identified challenges above.

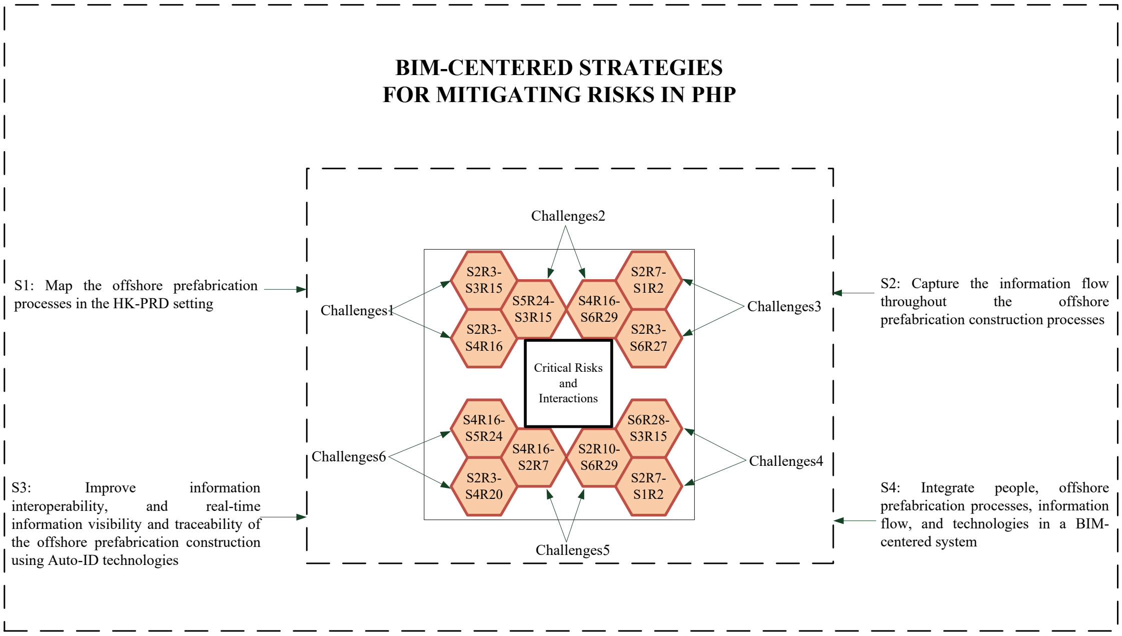

Figure 6. Framework for understanding risks, challenges, and proposed strategies

Strategy 1: Map PHP processes in the HK–PRD setting

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Efforts should be spent to understand the whole process and relevant constraints because of the separation of design, manufacturing, storage, transportation, and assembly. Previous studies have explored the processes in construction project management to appropriately plan resource allocation (Hegazy, 1999). However, the management skills and relevant information required by prefabrication construction differ significantly from those required by on-site projects often encountered in the construction industry. Strategy 1 thus aims to map the offshore prefabrication processes mainly concerned with HKHA (Hong Kong Housing Authority), especially in the HK–PRD setting, for further analysis.

The prototype proposed above serves as a framework to map the offshore prefabrication processes, with additional efforts supposed to be spent on describing it in greater detail. Case studies in three offshore prefabrication plants, which are HKHA's key producers (Yau Lee Wah, Shenzhen Hailong, and Wing Hong Shun), should be conducted for this purpose. Case study research on these three companies allows the exploration and understanding of complex risks based on the collected primary data. The study can be considered a robust research method, particularly when a holistic, in-depth investigation is required. A combination of qualitative methods, including semi-structured interviews, focus group meetings, non-participant observation, field notes, and analysis of documents and materials, can be used to investigate the information flow throughout the processes.

Strategy 2: Capture the information flow throughout the PHP processes

The aspiration to enhance housing production by reengineering the offshore PHP processes requires all the involved parties, especially for HKHA and its associated entities, to align the

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whole processes based on the available information to make better decisions. Information is recognized as a new and core element for successful management. Mapping the offshore prefabrication processes in Strategy 1 allows the capture of the information flow throughout the offshore PHP processes. A data flow diagram (DFD) originally developed by IBM is adopted to facilitate this purpose. A DFD is a significant modeling technique for analyzing and constructing information processes. A DFD literally means an illustration that explains the course or movement of information in a process. Fisher and Shen (1992) used the tool to map the flow of data within a construction company with a view to facilitating better information management (Fisher and Shen, 1992).

We focus on using the DFD technique in three specific and critical scenarios, namely, prefabrication construction, cross-border logistics, and on-site assembly, which are mostly concerned by HKHA. First is the way the design information is composed and decomposed by designers and passed to the precast component plants. The analysis of the drawings identifies information, such as design drawing and rationales created using ArchiCAD or other BIM software. Parallel to this step is the order information from the client to the plant. Formal and informal communications (e.g., drawings, briefings, and emails) between different parties (e.g., client, designer, and manufacturer) involved in the offshore prefabrication construction processes are analyzed, captured, and mapped using DFD. The interoperability of information flow is of particular interest for aligning the processes.

Second is the information flow from storage to transportation and sites. The transportation of prefabrication building components to HKHA’s construction sites, such as Tung Tau Cottage Area East, is often outsourced to professional logistics companies. The professional logistics companies are responsible for loading, fastening, and unloading the prefabrication building components, as well as customs clearance. The information flow can be captured by analyzing the contracts between the plants and the logistic companies and their working files for custom clearance. Maintaining the real-time information visibility and traceability of the precreation components is critical to ensure a smooth logistic and supply to the sites.

Third is the information flow from factory to on-site assembly. Owing to the compact sites in Hong Kong, the prefabricated components must reach the construction sites in a well-planned manner to fit the on-going job on site. Therefore, real-time information visibility and traceability is critical, and the sequence and positions of prefabricated components should be well-organized. This part of the information flow can be captured by analyzing the working files, drawings, and field notes and through non-participant observation and semi-structured interviews with site managers. Such information is significant for HKHA to work out high-level decision-making after feeding back to BIM or Housing Construction Management Enterprise System (HOMES) developed by HKHA to facilitate the management of housing production.

Strategy 3: Improve information interoperability and the real-time information visibility and traceability of the offshore PHP using auto-ID technologies

In Strategy 3, the information identified in the DFD is structured, stored, retrieved, visualized, and traced in a real-time manner in support of various types of decision-making within HKHA. This step is accomplished by adopting auto-ID technologies, such as barcode, QR code, RFID, and magnetic strip. RFID technology is promising in capturing real-time information among prefabrication manufacturing, logistics, and on-site construction. RFID tags are used to store the information as identified in Strategy 2. RFID writers with USB connection to computers help write the information into the tags. The information in the tags should be brief enough; for example, only a serial code should be present, whereas its complex structure as stated in the DFD should be put in a backend system. The rationales are (a) to ensure security and (b) to use the processing power provided by the backend system. RFID readers (e.g., handshaking devices) are used to retrieve the information from both the tags and the backend system. Programming based on the application programming interfaces (APIs) of RFID are needed to fulfill the functions.

A caveat is that RFID may eventually be incapable. Research has reported its incapability in construction; for example, radio frequency fails in steel members, and the reading distance is a problem (Lu et al., 2011). This incapability should be overcome by carefully selecting appropriate models of RFID, namely, active or passive RFID and low or high frequency RFID. Cost is another issue, particularly when RFID technology is massively applied in offsite construction. Experiments in both a controlled environment and real-life construction sites are conducted. For example, HKHA has deployed its public housing projects as experimental projects for RFID technology, which are a good chance to contribute and collect information. Although RFID technology is mainly discussed here; other auto-ID technologies, such as QR codes, can also serve as alternatives.

Strategy 4: Integrate people, offshore prefabrication processes, information flow, and technologies in a BIM-centered system

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This strategy is developed to integrate people, offshore prefabrication processes, information flow, and technologies in a BIM-centered system from technical perspective, which can be understood as a real instance of the significantly discussed Internet of things (IoTs). To connect the RFID subsystem to the BIM subsystem, a gateway should be developed. Graphically, this connection can be considered to be a gateway between BIM and the backend system, as shown in Figure 7. Data exchange protocols should be developed at a lower level, whereas an API at a higher level can enable information synchronization between the two sub-systems. The data exchange protocol is proposed to be based on the standard of the industry foundation classes (IFC) in view of the interoperability of the gateway subsystem. As a major data standard for BIM, IFC, which is published by the International Alliance for Interoperability (IAI), serves an important role in the process because it is a standard for sharing data throughout the project lifecycle, globally, across disciplines, and across technical applications in the construction industry. Again, the information collected in Strategy 2 and mapped in the DFD is incorporated into the BIM subsystem. Various APIs have been developed to enable further developments in BIM software, such as ArchiCAD, AutoCAD, Revit, or NavisWork, allowing their connection to the auto-ID subsystem. Enabling the BIM subsystem to “talk” to the building components through auto-ID technologies and respond to users’ intervention when needed is of particular interest. Microsoft Visual Studio is the ideal programming environment to develop the gateway.

After the auto-ID subsystem and the gateway are developed, their functionalities are encapsulated for industrial users. Computer technologies, such as Google Sketch Up and Microsoft Visual Studio, can be used to develop such an operable system. All these

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technologies, such as SCOs, RFID, wireless, and BIM, are significantly discussed and experimented in the construction industry. What is innovative here is to organize them in a cohesive way to improve the current offshore PHP processes. Furthermore, all of the abovementioned technologies have not been fully available and are subject to further development. The integration can transform and upgrade the managerial level of HKHA and the construction industry in Hong Kong and PRD into a type that is real-time, interoperable, and closed-loop.

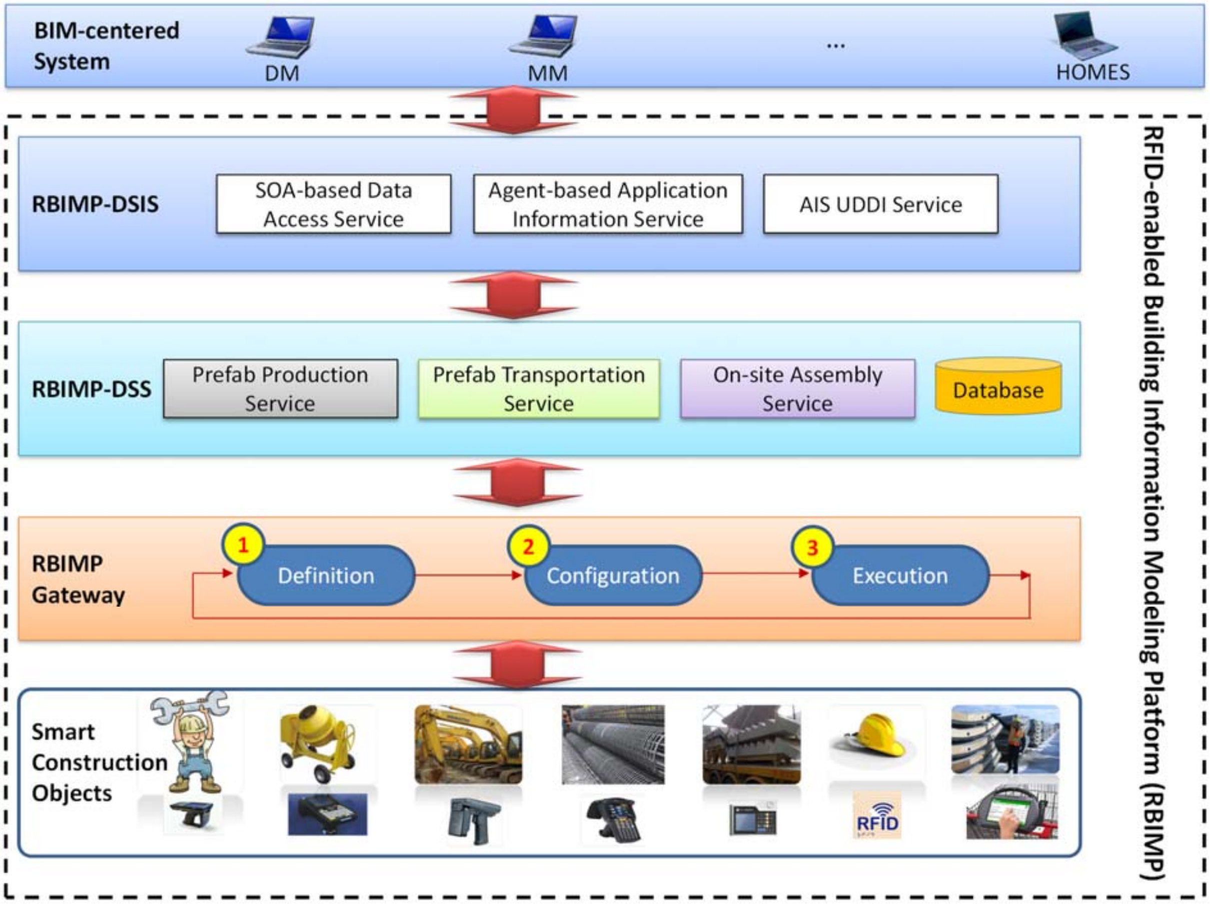

Figure 7. Overview of RBIMP

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As shown in Figure 7, the proposed RBIMP consists of four major components, including smart construction objects (SCOs), RBIMP Gateway, RBIMP decision support service (RBIMP-DSS), and RBIMP data source interoperability service (RBIMP-DSIS), to seamlessly integrate RBIMP into HKHA's current information architecture. From the bottom to the top, SCOs are construction objects from HKHA's business partners, such as construction sites, in which typical construction resources are equipped with RFID devices and converted into "smart" objects. RBIMP Gateway connects, manages, and controls the SCOs by defining, configuring, and executing the construction logics. RBIMP-DSS is made to suit the prefabrication housing construction in Hong Kong. Three key phases, including prefabrication manufacturing, prefabrication logistics, and onsite construction, are identified to match the vision of HKHA. To enhance the data sharing and interoperability among BIM, HOMES, and RBIMP, an XML-based data sharing mechanism is used for the design of RBMIP-DSIS. Under the system, decision-making systems such as BIM and HOMES in HKHA are able to use the real-time data for advanced decision-making. By developing the proposed RBIMP through the implementation of four detailed strategies, identified challenges can be solved, and the critical risks and interactions can be effectively mitigated.

5.3 Validation of the effectiveness of the strategies

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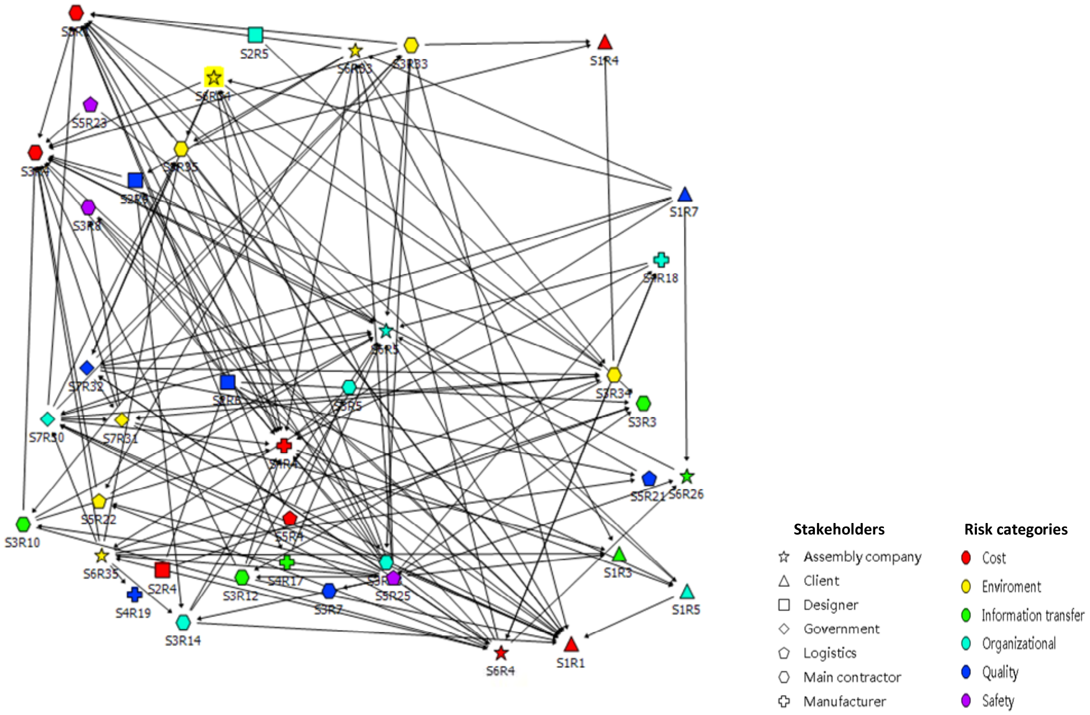

Figure 8. Risk network after mitigating critical risks and interactions

By recalculating the key SNA indicators, this section illustrates an immediate simulation of the stakeholder issue network after the implementation of the proposed strategies in the above section. An important assumption here is that all of the proposed strategies are effectively implemented, and corresponding critical risks and interactions are eliminated. The simulation serves as a reference tool to test the effectiveness of the suggested strategies and to predict the potential of network complexity reduction. After the suggested strategies are performed mainly by resolving the critical risks and links in Table 5, the network in the case study is reduced to a structure of 40 nodes and 151 interactions, as shown in Figure 8. In comparing this network to the initial network in Figure 3, three observations can be made: (1) The network is less condensed by reducing the links considerably. (2) The number of isolates increases, implying that more stakeholder risks can be handled individually without propagating effects. (3) The dyadic interactions increase where they are easier to be managed through the consideration of the particular 151 cause-and-effect relations. The reduced network complexity is also reflected by the values of network properties. The density and cohesion of the network in Figure 8 are 0.097 and 0.071, respectively. Compared with the original network density and cohesion of 0.225 and 0.962, respectively, these values are reduced by 90.3% and 92.9%, respectively. The betweenness centrality values for both risks and links are largely reduced compared to the values in Table 6. According to the simulation results, the suggested strategies are useful to decrease the network complexity and therefore improve the effectiveness of the stakeholder management process. In evaluating their usefulness from a more practical perspective, continuous monitoring and assessment of the network dynamics is deemed necessary. The performance of the mitigation actions should be reviewed and monitored periodically in the future.

Table 6. Top risks and interactions after risk mitigation

Rank	Node Betweenness Centrality			Link Betweenness Centrality		
	Original	After	Change	Original	After	Change
1	0.127	0.082	-35.6%	51.5	49	-4.9%
2	0.080	0.054	-33.4%	51.2	43	-16.0%
3	0.069	0.039	-43.0%	51.1	29.9	-41.5%
4	0.061	0.022	-63.4%	38.5	25.5	-33.8%
5	0.054	0.020	-62.1%	36.4	21	-42.3%
6	0.049	0.018	-62.8%	34.8	20.8	-40.2%
7	0.047	0.017	-64.6%	34.6	20.8	-39.9%
8	0.046	0.016	-65.7%	32.4	20.2	-37.7%
9	0.041	0.015	-63.3%	32.1	19.7	-38.6%
10	0.041	0.013	-68.4%	29.5	18.8	-36.3%

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6 Conclusion

The need to look into the potential risks that cause project delay and the absence of a systematic analysis method for stakeholder risks and their interrelations in PHP is a reason that motivates this study. Through social network theory and classical stakeholder management approach, this study investigated the underlying network of stakeholder risks in PHP using SNA and identified key risks and interactions that exert high influences on other risks directly or indirectly. Network variables and analytical procedures were illustrated in detail and were demonstrated by PHP projects in Hong Kong. Built on the theoretical assumption that network complexity can be decreased by removing key nodes and links, several BIM-centered strategies were suggested to improve stakeholder coordination in PHP, which would ultimately help to address stakeholder risks and eliminate risk relationships highly interconnected with other risks. Network density and cohesion were recalculated to simulate the effectiveness of the suggested strategies. The use of SNA in modeling and deciphering the stakeholder issue network can break the barriers of conventional stakeholder analysis. This research is valuable in providing an effective tool for the evaluation of potential risks that can lead to schedule delay in all the processes of PHP, such that corresponding strategies can be developed and used against them to ensure the efficient management of prefabrication construction.

Limitations and further research of this topic area should mainly focus on the following two aspects: (1) As a lack of effective framework for the analysis of cost/benefit effect on risk mitigation actions, future research regarding to the development of analytical framework for simulating the effectiveness of risk mitigation actions should be conducted, such that optimized

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risks mitigation action can be identified under different resource constraints; (2) As it is ideal to engage all stakeholders in the prefabrication housing production project to improve the quality and accuracy of stakeholder issue analysis, more case studies should be conducted to consolidate the findings of this research.

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