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Evaluating different stakeholder impacts on the occurrence of quality defects in offsite construction projects: A Bayesian-network-based model

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Abstract

Offsite construction has been identified as an effective approach for enhancing the sustainability of the construction industry. However, due to the fragmented production processes of offsite construction, quality defect control has become a significant challenge in the promotion of offsite construction projects. Offsite construction projects involve multiple interdependent stakeholders in close collaboration. These stakeholders play various roles in quality management and have different degrees of impact on the occurrence of quality defects. To enhance quality defect management in offsite construction projects, it is important to evaluate the different stakeholder impacts on the occurrence of quality defect. Through impact evaluations, critical stakeholders can be identified and their responsibilities clarified with respect to project quality, thereby motivating these key stakeholders to improve their quality defect control. In this study, we developed an evaluation model using the Bayesian network approach to measure stakeholder impacts on defect occurrence in offsite construction projects. Quality defects and stakeholder-related factors that might incur defects were modeled as a Bayesian network and the dependencies among network nodes examined. Then, the stakeholder impacts on the occurrence of quality defects were evaluated using Bayesian analysis. Finally, this Bayesian-network-based evaluation model was applied to a real project in Shenzhen, China. The results indicate that use of precast components with quality defects, misoperations by construction workers, and ineffective quality inspection and testing during onsite assembly and construction were the major factors affecting quality defect control. Additionally, in this case study, we found the contractor to have the highest level of impact on the occurrence of quality defects. This study contributes to the fields of stakeholder impact evaluation and quality defect analysis, and links defect management with key project stakeholders.

1. Introduction

Offsite construction refers to a construction method that enables practitioners to manufacture building components in controlled factories, and then to assemble these components at the construction site (Jiang et al., 2018b). Offsite construction technologies have been widely adopted in the construction industry and range from prefabricated components to whole modular building (Gibb,1999; Pan et al., 2008). Compared with projects that use in-situ construction, offsite construction projects (OCPs) can achieve better sustainability performance in a few dimensions, including construction efficiency, delivery time, labor expenditure, safety, energy conservation, water conservation, material conservation, land conservation, waste mitigation, and environmental protection (Jiang et al., 2018b; Li et al., 2016; Xue et al., 2018). For example, according to Tam et al. (2007), construction wastes in Hong Kong could be mitigated by up to 84.7% if offsite construction method is adopted. Based on life cycle assessment, Aye et al. (2012) argued that compared with in-situ construction, the adoption of a steel-structured offsite construction system could result in reduced material consumption of up to 78%. Based on case studies, Mao et al. (2013) found that the adoption of offsite construction can help practitioners to reduce greenhouse gas emissions in residential buildings by roughly 8.7%.

In light of these sustainability benefits, both developed and developing countries, including Japan, the UK, Ireland, Scotland, Australia, China, and Nigeria, have made efforts to promote OCPs in their construction industries (Jiang et al., 2018b; Arif et al., 2012; Blismas and Wakefield, 2009; Jansson, 2010; Rahimian et al., 2017). As offsite construction has gained prominence, there is an increasing demand for guaranteed OCP quality performance (Kim et al., 2016; Zheng et al., 2016). In countries that experience construction quality problems and who have identified offsite construction as a way to improve quality, it is critical that quality defects in OCPs (including design defects, offsite production defects, and onsite assembly and construction defects) be effectively controlled and mitigated (Zheng et al., 2016; Rahimian et al., 2017).

Due to the fragmented nature of offsite construction, mitigating the quality defects of OCPs requires close collaboration among project stakeholders. An OCP typically involves a series of activities including design, offsite manufacturing, transportation, and onsite assembly and construction (Jaillon and Poon, 2009). A number of stakeholders participate in and are responsible for these project activities (Xue et al., 2018). Due to the dependencies among different project activities, the successful delivery of an OCP requires a joint effort by multiple stakeholders including the developer, designer, precast component (PC) manufacturer, PC transportation company, and contractor (Li et al., 2016; Xue et al., 2018; London and Pablo, 2017; Jiang et al., 2016; Teng et al., 2017). Due to the dependencies among stakeholder activities, quality defects caused by one stakeholder can significantly influence the quality performance of other stakeholders. For example, dimensional deviations in the PCs caused by the manufacturer can adversely affect the quality performance of the construction contractor (Su et al., 2016b). Accordingly, in a defect management plan, key stakeholders must be identified and their interdependencies analyzed with respect to quality performance.

As different stakeholders have different dependency relationships and play different roles in defect management, it is important to accurately evaluate the potential impact of each stakeholder group on the occurrence of quality defects (Heravitorbati et al., 2011). First, a stakeholder impact evaluation can help identify the most critical stakeholders (Olander, 2007). These stakeholders can significantly affect the quality performance of the OCP. To mitigate quality defects, project managers can then focus on the effective management of these critical stakeholders. Second, evaluating stakeholder impacts can help to gauge the quality-related responsibilities of different stakeholders when quality defects emerge (Lu, 2014). Given the dependencies among the quality performances of stakeholders, a quality defect can have linkages with multiple stakeholders, which makes it difficult to judge the degree to which a certain stakeholder is responsible for a given defect (e.g., Su et al., 2016b). In a quality management plan, the potential impact of a stakeholder can be an important reference for determining the degree of responsibility of that stakeholder for project quality (Lu, 2014). A clear division of quality responsibilities can motivate corresponding stakeholders to enhance their efforts toward defect control (Peterson, 2007; Lu, 2014). Accordingly, there is an urgent need to evaluate the impacts of different stakeholders on the occurrence of quality defects in OCPs.

In fields related to OCP defect management, the majority of studies have focused on defect detection (e.g., Kim et al., 2016; Wang et al., 2016) and defect analysis (e.g., Su et al., 2016a; Qi et al., 2016). Very few researchers have investigated OCP quality defects from a stakeholder perspective. As such, the majority of existing defect management studies provide no effective methods for practitioners to evaluate stakeholder impacts on the occurrence of OCP quality defects. When evaluating stakeholder impacts, traditional stakeholder evaluation methods such as the stakeholder index (Olander, 2007) and the interest/power matrix (Olander and Landin, 2005) cannot be used to investigate the dependencies among different stakeholders with respect to quality performance. These methods may overestimate or underestimate the actual impacts. For example, if a designer's impact on defect occurrence is evaluated without any consideration of the dependency between design and PC production, the impact of the designer will be misestimated. To address these research gaps, in this study, we used a Bayesian network to assess the different stakeholder impacts on quality defects in OCPs. Stakeholder-related factors that may incur quality defects were modeled with consideration given to stakeholder dependencies. We then conducted a Bayesian analysis to assess stakeholder impacts on the occurrence of quality defects. Finally, we conducted a case study to demonstrate the application of this Bayesian-network-based model. 2. Literature review

2.1. Managing quality defects in OCPs

Quality is one of the most important objectives of project management (Basu, 2014). Compared with projects using in-situ construction, OCPs are expected to achieve better quality performance because the PCs are manufactured in factories, which enables manufacturers to achieve better quality control (Jiang et al., 2018b; Li et al., 2016). Since OCPs involve a number of activities (e.g., offsite manufacturing) and technologies (e.g., PC production technology) that do not occur in traditional construction projects, the processes, methods, and practices of OCP quality management differ from those of traditional construction projects (Su et al., 2016b). First, compared with projects using in-situ construction, quality defects due to environmental factors (e.g., defects related to concrete maintenance due to lack of humidity) can be effectively mitigated in OCPs because the temperature, humidity, and pH values of PC factories can be well controlled during the manufacture of PCs (Jiang et al., 2018b; Li et al., 2016). Second, the tolerance of dimensional defects in OCPs is lower than that of traditional construction projects because dimensional defects can significantly affect the quality performance of onsite assembly (Su et al., 2016b). Third, in OCPs, the quality-related responsibilities of contractors are partially transferred to the PC manufacturers (Cao et al., 2018). Fourth, the onsite assembly processes of OCPs are more complex than those of traditional projects, which means that more quality issues related to onsite assembly will emerge in OCPs (Su et al., 2016a).

A number of studies have been conducted to investigate the quality management practices of OCPs (e.g., Su et al., 2016b; Qi and Li, 2014; Zhou et al., 2016). The focus of these studies has been on quality performance evaluation (e.g., Qi and Li, 2014), quality management framework (e.g.), defect detection (e.g., Kim et al., 2016), and defect analysis (Su et al., 2016b). The purpose of this study is to evaluate stakeholder impacts on the occurrence of quality defects in OCPs. Therefore, in this section, studies related to defect management, i.e., defect detection and analysis, are reviewed. In terms of defect detection, scholars have focused on developing advanced inspection methods for accurately detecting quality defects in real time. Kim et al. (2016) developed a noncontact dimensional quality assurance method for detecting quality defects in PCs based on laser scanning and building information modeling (BIM). This method has been applied and validated in field tests on two full-scale precast slabs. Wang et al. (2017) employed colored laser scan technology for the automated position estimation of PCs. Compared with the study conducted by Kim et al. (2016), the method proposed by Wang et al. (2017) focused on quality defects in the connections between adjacent PCs rather than those in the PCs themselves. Zhong et al. (2017) utilized advanced information technologies, including BIM, geographic information system (GIS), and radio frequency identification (RFID), to develop an Internet-of-Things-based platform to manage OCPs in Hong Kong. These researchers argued that this platform has the potential for detecting and controlling quality defects in OCPs in real time. The platform established by Zhong et al. (2017) focused on the whole lifecycle management of OCPs, which is more comprehensive than the two aforementioned studies. Generally speaking, the defect detection literature is typically technologyoriented.

With regard to defect analysis, scholars have focused on identifying and analyzing factors that may incur quality defects in OCPs. According to Su et al. (2016a), quality defects in OCPs can be classified into four categoriesddesign defects, PC defects during manufacturing, PC defects due to transportation, and quality defects during onsite assembly and constructiondwhich correspond to the stakeholder-related activities of design, manufacturing, transportation, and onsite assembly and construction, respectively. Some studies in this area have focused on just one type of quality defect in OCPs. For example, Jaillon and Poon (2010) conducted questionnaire-based surveys and case studies to analyze the design defects in prefabricated housing projects (a type of OCP) in Hong Kong. Their findings revealed that lack of design knowledge, such as lifecycle design, significantly restricted the application of prefabricated housing in Hong Kong. Based on structure equation modeling, Zheng et al. (2016) identified critical factors that could incur PC defects during the OCP manufacturing stage, and then investigated the interrelationships among these factors. These authors identified a lack of mature methods for PC production as the most important factor adversely affecting the quality performance of PC manufacturing. Based on a field study, Qi et al. (2016) analyzed factors that led to quality defects during onsite assembly and construction. These researchers argued that standardization of design, technical instructions for quality management, worker training, and traceable defect inspection should be enhanced to mitigate quality defects in OCPs. In general, studies that focus on one type of quality defect cannot provide a comprehensive defect management scheme covering the whole lifecycle of OCPs. Additionally, the interdependencies among quality defects at different project stages have been ignored, which may limit the effectiveness of defect management (Su et al., 2016a).

To address this research gap, some defect analysis studies have investigated multiple types of quality defects in OCPs. For instance, Liu (2016) analyzed OCP quality defects in design, manufacturing, and transportation activities, and found that lack of design standardization and lack of effective operation instructions for running PC production lines may cause quality defects in OCPs. Based on a site survey in the city of Jinan, China, Su et al. (2016b) employed an Ishikawa diagram to identify and analyze factors that lead to quality defects in OCPs. These authors argued that unqualified staff, equipment failures, low-quality materials, and lack of effective assembly methods were important factors that have resulted in OCP quality defects. From the perspective of lean construction, Zhou et al. (2016) investigated the occurrence of quality defects over OCP lifecycles. Their investigation revealed that standardization, the skill and experience of staff, process control, performance evaluation, and continuous improvement were the most critical factors affecting the occurrence of quality defects in OCPs. Generally speaking, we found that studies that integrate multiple types of quality defects can provide a relatively comprehensive understanding of the defect management of OCPs. Therefore, in this study, we investigated multiple types of defects when evaluating the impacts of stakeholders on defect occurrence. Based on this review of relevant studies, Table 1 summarizes the factors affecting the occurrence of quality defects in OCPs.

From Table 1, we can see that a number of defect analysis studies have been conducted to answer questions related to “what”, i.e., “what can affect the occurrence of quality defects in OCPs?” The findings of these studies can help identify potential directions for defect control. Based on these directions, practitioners can take corresponding actions to mitigate quality defects in OCPs according to their abilities to affect the occurrence of quality defects.

2.2. Evaluating stakeholder impacts on the occurrence of quality defects in OCPs

In practice, the majority of factors identified in Table 1 are controlled, determined, or significantly affected by two or more stakeholders. Similar to the work of Tang et al. (2013), in this paper, factors with close linkages to project stakeholders are denoted as stakeholder-related factors. By affecting stakeholder-related factors, relevant stakeholders can influence the occurrence of quality defects in OCPs. Given the dependencies among stakeholders, quality defects caused by a given stakeholder can affect the quality performance of others (Su et al., 2016a). To improve the control of defects by stakeholders, it is necessary to evaluate the impacts of different stakeholders with respect to their dependencies. By evaluating stakeholder impacts on defect occurrence, critical stakeholders can be identified and the responsibility of each for the OCP quality can be assessed (Olander, 2007), which will then motivate corresponding stakeholders to take action to mitigate the occurrence of defects (Peterson, 2007; Lu, 2014).

In terms of evaluating stakeholder impacts, studies in the field of construction project management typically focus on stakeholder attribute analysis, which stems from the salience theory developed by Mitchell and Agle (1997). According to the study conducted by Mitchell and Agle (1997), the impact of a stakeholder can be effectively measured by his inherent characteristics. From this perspective, the core of any stakeholder evaluation is to identify critical attributes. In the study conducted by Olander and Landin (2005), the stakeholder attributes of power and interest were used to evaluate stakeholder impacts in construction projects. The authors referred to these two attributes as key indicators for measuring the vested interests of stakeholders. In the empirical investigation performed by Mojtahedi and Oo (2017), three stakeholder attributes, i.e., power, legitimacy, and urgency, were employed to measure the impact of each stakeholder in disaster recovery projects. These three attributes were directly borrowed from the salience theory (Mitchell and Agle, 1997). Consistent with the work of Mojtahedi and Oo (2017), the same three stakeholder attributes were used by Li et al. (2018b) in a stakeholder impact analysis of green building projects. By integrating these three attributes with the vested interests of stakeholders, Olander (2007) developed a stakeholder index for measuring stakeholder impacts in construction projects. Researchers such as Nguyen et al. (2009) and Yu et al. (2019) have used this stakeholder index in their stakeholder evaluations. In the research conducted by Aragones- Beltran et al. (2017), stakeholder impacts on project management

Table 1

Factors affecting the occurrence of quality defects in OCPs.

Project activities	Factors affecting the occurrence of quality defects	Source
Design	Misoperations by designer	Su et al. (2016a)
	Lack of skill and experience related to OCP design	Su et al. (2016a); Liu (2016); Ismail (2017)
	Lack of information input from developer	Liu (2016); Ismail (2017)
	Lack of OCP design standard	Liu (2016); Qi et al. (2016); Zhou et al. (2016); Ismail (2017)
Offsite manufacturing	Lack of mature production methods, processes and workmanship	Zheng et al. (2016); Su et al. (2016b); Qi et al. (2016); Zhou et al. (2016); Ismail (2017); Wang et al. (2018)
	Lack of operation instruction or handbook for PC production	Zheng et al. (2016); Su et al. (2016b); Liu (2016)
	Lack of skill and experience related to PC production	Su et al. (2016b)
	Misoperations by workers	Su et al. (2016b); Liu (2016); Qi et al. (2016)
	Equipment failures	Zheng et al. (2016); Su et al. (2016b)
	Use of low-quality materials	Zheng et al. (2016); Su et al. (2016b); Liu (2016); Wang et al. (2018)
	Lack of quality management system for PC production	Zheng et al. (2016); Qi et al. (2016); Yin et al. (2009)
	Ineffective quality inspection and testing during PC production	Zheng et al. (2016); Su et al. (2016b); Liu (2016); Kim et al. (2016); Wang et al. (2017); Yin et al. (2009)
	Poor production environment	Zheng et al. (2016); Su et al. (2016b)
	Ineffective storage management	Su et al. (2016b); Su et al. (2016a); Qi and Li (2014); Liu (2016); Qi et al. (2016)
Transportation	Unreasonable transportation plan	Liu (2016)
	Misoperations by transportation drivers and workers	Interview
	Equipment failures	Liu (2016)
Onsite assembly and construction	Lack of skill and experience related to OCP	Su et al. (2016b); Liu (2016); Qi et al. (2016); Zhou et al. (2016); Yu (2017); Tam et al. (2015)
	Insufficient technical disclosure	Su et al. (2016b); Qi and Li (2014); Yu (2017); Tam et al. (2015)

Misoperations by construction workers	Su et al. (2016b); Qi et al. (2016)
Use of PCs with quality defects	Su et al. (2016b)
Lack of operation instruction or handbook for onsite assembly and construction	Su et al. (2016b); Qi and Li (2014); Qi et al. (2016); Zhou et al. (2016);
Lack of onsite quality management system	Qi and Li (2014); Qi et al. (2016); Yu (2017); Tam et al. (2015)
Equipment failures	Su et al. (2016b)
Unreasonable assembly and construction plan	Interview
Ineffective onsite storage management	Su et al. (2016b); Liu (2016)
Ineffective quality inspection and testing during onsite assembly and construction	Su et al. (2016b); Yu (2017); Li et al. (2018a); Tam et al. (2015)

and project outcomes were assessed based on the stakeholder attributes of knowledge, social skills, assets, and external stakeholder features.

Generally speaking, attribute-based studies evaluate stakeholder impacts based on the inherent features of stakeholders, without consideration of their interdependencies. Such evaluation methods can result in the overestimation or underestimation of stakeholder impacts, and are not applicable to this study. In OCPs, a stakeholder can affect the occurrence of quality defects through direct participation, as well as the quality of the performance of activities in which he/she is not directly involved due to the dependencies among stakeholder activities. For example, the defect management of a PC manufacturer can directly affect the quality performance of PC production and indirectly affect the quality performance of onsite assembly and construction. Therefore, to evaluate different stakeholder impacts on defect occurrence in OCPs, researchers should comprehensively investigate stakeholder dependencies.

3. Model development

3.1. Research method

To fulfill the research objective of this study, the Bayesian network was employed. The Bayesian network, also called the belief network, has been widely applied to address complex quality management issues in multistage production environments (e.g., Nguyen, 2015; Musella and Vicard, 2015). Offsite construction is a typical multistage production process that involves design, offsite manufacturing, transportation, and onsite assembly and construction. Therefore, the Bayesian network is applicable to the quality management issues of OCPs. Furthermore, application of a Bayesian network enables researchers to analyze multi-factor systems with complex factor dependencies. Based on this research method, dependencies among the quality performances of stakeholders in OCPs can be effectively investigated and modeled. In addition, given that the dependencies between offsite and onsite activities are characterized by uncertainties (Arashpour et al., 2016), the Bayesian network can be utilized to analyze these uncertainties (Jensen, 2002). Accordingly, the Bayesian network was determined to be an effective method for realizing this study's research objective.

Fig. 1 shows the overall research design of this study. We analyzed the literature regarding the quality defects of OCPs to identify research gaps and compared the methods available for evaluating stakeholder impact (i.e., stakeholder-attribute-based methods and Bayesian network), from which we identified the Bayesian network as the most effective approach. Next, to investigate the occurrence of quality defects in OPCs, we established a model based on the Bayesian network to model the quality defects and causal stakeholder-related factors. Using this model, different stakeholder impacts on the occurrence of defects were quantified using Bayesian analysis. Finally, we conducted a case study to demonstrate and test the practical values of the Bayesian-networkbased model. The data in this case study were collected via interviews with key project participants.

3.2. Modeling the occurrence of quality defects in a Bayesian network

Similar to previous studies that have employed the Bayesian network in quality defect analysis (Nguyen, 2015; Musella and Vicard, 2015), in this study, we assumed that the graph of the Bayesian-network-based model is acyclical with respect to dependencies among different stakeholder-related factors. This assumption is consistent with the real-world scenarios of defect

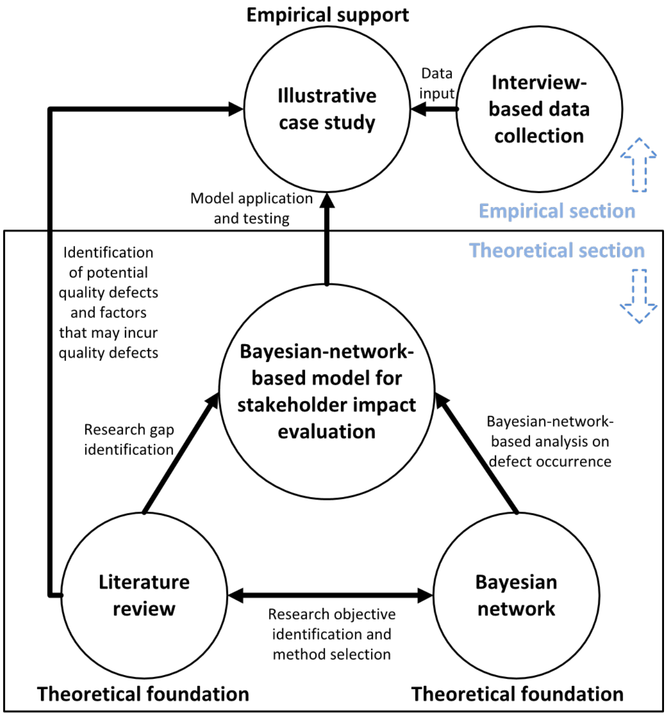

Fig. 1. Research framework of this study.

management because construction projects comprise once-off activities with a very limited number of dual feedbacks (Arashpour et al., 2016). In OCPs, industrialized production processes are employed to deliver building products (Mao et al., 2013). The basic assumption of the Bayesian network can be adopted in the quality defect analysis of an industrialized production line (Nguyen, 2015; Musella and Vicard, 2015). Therefore, this assumption is applicable to the current study.

A Bayesian network consists of nodes and edges, wherein nodes represent a set of random variables and edges reflect the conditional dependencies between nodes (Jensen, 2002). If node A has a direct edge to B, then A is labeled as a parent of B, and B is labeled as a child of A. Nodes without parents are called roots. An edge from A to B indicates that A can affect B. If node A can influence node C directly (through an edge) or indirectly (by affecting other nodes that have an edge to C), then C is referred to as a reachable node for A.

As shown in Fig. 2, in this study, the nodes in the Bayesian network represent either quality defects at different project stages or stakeholder-related factors that may incur quality defects. Edges indicate casual relationships among different nodes. Four types of basic edges emerge in the Bayesian-network-based model, i.e., edges from factor to factor, edges from factor to defect, edges from defect to defect, and edges from defect to factor. Thus, a Bayesiannetwork-based model that maps the occurrence of quality defects in OCPs can be developed based on multiple combinations of such nodes and edges.

In Bayesian networks, the probability distribution of a node's state can be determined based on the state of its neighboring nodes that have edges directly pointing to this node (Neapolitan, 2004). Consistent with Ding and Xu (2018) and Neumeier et al. (2018), in this study, a node in a Bayesian network can have two states: "event occurring (State1, ST1)" or "not occurring (State0, ST0)". For example, the use of low-quality materials can be an important node in the Bayesian-network-based model because these materials may incur quality defects in OCPs. If the state of this node is "event occurring," then this indicates that stakeholders are using lowquality materials in the current OCP. If the state is "not occurring," then it means that the stakeholders are not using low-quality materials in this project. The state of a node can be estimated based on the state of its parents. For the example shown in Fig. 2, nodes F_x and F_y are the parents of QD_i. When the states of F_x and F_y are determined (e.g., not occurring, ST0), the state of QD_i (e.g., event occurring, ST1) in the Bayesian network can be calculated as shown in Eq. (1) (Neumeier et al., 2018):

PQDi¼ST1jFx¼ST0;Fy¼ST0¼PQDP~~i ¼FSTx ¼1ST;Fx0¼;FSTy ¼0;STF~~y0¼ ST0

(1)

¼ P$_{\text{Fz; QDj2fST0; ST1g}}$PQDi ¼ ST1; Fx ¼ ST0; Fy ¼ ST0; Fz; QDj

P$_{\text{QDi; Fz; QDj2fST0; ST1g}}$PFx ¼ ST0; Fy ¼ ST0; QDi; Fz; QDj

To demonstrate the impacts of parent nodes on corresponding child nodes, researchers typically use conditional probability tables (CPTs) to reflect the strength of the edges (i.e., conditional dependencies) between directly connected nodes (Tang and McCabe, 2007; Neapolitan, 2004). For instance, if node A is a child of node B, then the CPT will contain the conditional probability of node A's state, given that node B has occurred (and not occurred). For a node without any parents, the CPT displays the estimated probability distribution of the node's state. For a node with parents, the CPT displays the estimated probability distribution of the node's state, given all possible parent states. For example, in Fig. 1, F_x and F_y are the parents of QD_i, and Table 2 shows the CPT of QD_i. During data collection in the case study, we used CPTs to record the probability distributions of nodes in the Bayesian network.

3.3. Evaluating the potential impacts of different stakeholders on defect occurrence

Based on the CPTs, the potential impact of a stakeholder-related factor (e.g., F_x) on a given quality defect (e.g., QD_i) can be evaluated, as shown in Eq. (2):

IMðFx; QDiÞ¼j~~PðQDⁱ ¼ ST0jFˣ ¼ ST1Þ PðQDÞⁱ ¼ ST0jFˣ ¼ ST0Þj PðQ~~D$_i$ ¼ ST0

(2)

PðQD$_i$ ¼ ST0Þ indicates the probability that quality defect QD_i does not occur in the OCP. PðQD$_i$ ¼ ST0jF$_x$ ¼ ST1Þ denotes the probability that quality defect QD_i does not occur, given occurrence of F_x. PðQD$_i$ ¼ ST0jF$_x$ ¼ ST1Þ denotes the probability that quality defect QD_i does not occur, given no occurrence of F_x. When the state of F_x changes, IMðF$_x$; QD$_i$Þ reflects the gap in the probabilities of successfully avoiding quality defect QD_i, given the occurrence and no occurrence of F_x. This gap can reflect the potential impact of F_x on the occurrence of QD_i.

Suppose that n types of stakeholders are involved in the OCP, the set of stakeholders can be defined as fS$_{1;}$ S$_{2;}$ /; S$_{i;}$ /; S$_{n}$1$_{;}$ S$_{n;}$ g. The set of S_i -related

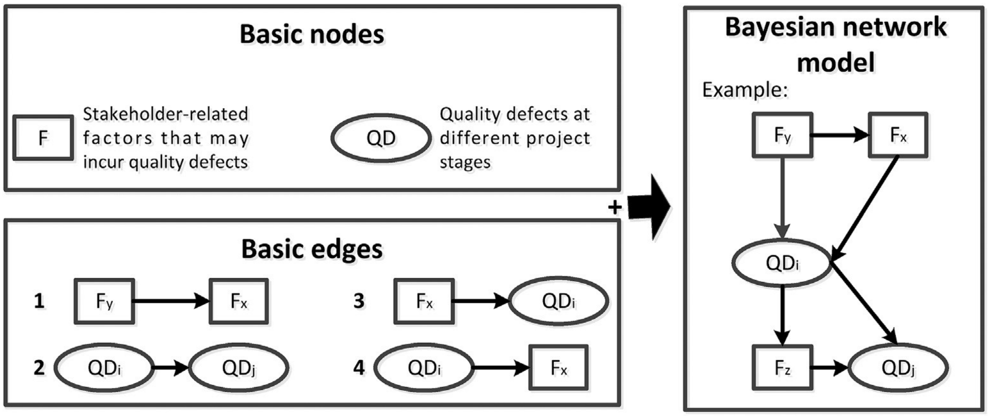

Fig. 2. Quality defect model based on a Bayesian network.

factors can be denoted as S_i F. As in the work of Tang et al. (2013), the principles of S_i F selection stipulate that if a factor belongs to S_i F, then: 1) the state of this factor can be directly controlled by S_i , or 2) S_i has the power to affect this factor and is responsible for managing this factor according to project contracts. In some cases, a factor in S_i F may have linkages with other stakeholders. The strength of the linkage between S_i and this factor is denoted as v_i , where Pv$_i$ ¼ 1. By influencing the state of the factors in S_i F, S_i can affect the occurrence of quality defect QD_i. The potential impact of S_i on QD_i can be evaluated as shown in Eq. (3):

AQðS$_i$; QD$_i$Þ¼ X v$_i$, IMðF$_m$; QD$_i$Þ (3)

F$_m$2S$_i$ F

In terms of controlling the occurrence of QD$_i$, the relative importance of S$_i$ can be evaluated as shown in Eq. (4).

RIðS$_i$; QD$_i$Þ¼________________ $_n$AQðS$_i$; QD$_i$Þ Þ(4)

P$_{k¼1}$AQðS$_k$; QD$_i$

4. Illustrative case study

4.1. Background information

In this study, we selected a campus expansion project to illustrate the application of the Bayesian-network-based model. This project is located on the south side of the Harbin Institute of Technology (HIT) in the Nanshan District of Shenzhen, China. The total floor area of this project is 101,053.15 m^2 and the total project cost is around 5,676,497.8 USD. The assembly rate (an indicator for measuring the degree of PC application in OCPs (Liu et al., 2018; Jiang et al., 2018a)of this OCP is 61.7%, which is relatively high in China. This high assembly rate indicates that a large percentage of the building components in this case study was produced using offsite construction. This project comprises five high-rise student dormitories and one three-story student canteen, for a total of six buildings. The five high-rise buildings have a shear wall structure, and the canteen has a frame structure. Both onsite and offsite construction technologies have been applied in this project. The basements and non-standard floors aboveground are being constructed by traditional cast-in-situ construction. The standard floors are being constructed using prefabricated structures, including non-load-bearing external walls, precast stairs, and parts of inner walls.

Table 2
Exemplar CPT of.QD$_i$

		(F$_x$, F$_y$)			
		(ST0, ST0)	(ST0, ST1)	(ST1, ST0)	(ST1, ST1)
QD$_i$	ST0	PðQD$_i$ ¼ ST0jF$_x$ ¼ ST0;F$_y$ ¼ ST0Þ	PðQD$_i$ ¼ ST0jF$_x$ ¼ ST0;F$_y$ ¼ ST1Þ	PðQD$_i$ ¼ ST0jF$_x$ ¼ ST1;F$_y$ ¼ ST0Þ	PðQD$_i$ ¼ ST0jF$_x$ ¼ ST1;F$_y$ ¼ ST1Þ
ST1		PðQD$_i$ ¼ ST1jF$_x$ ¼ ST0;F$_y$ ¼ ST0Þ	PðQD$_i$ ¼ ST1jF$_x$ ¼ ST0;F$_y$ ¼ ST1Þ	PðQD$_i$ ¼ ST1jF$_x$ ¼ ST1;F$_y$ ¼ ST0Þ	PðQD$_i$ ¼ ST1jF$_x$ ¼ ST1;F$_y$ ¼ ST1Þ

Six types of key stakeholders are involved in this project, i.e., the developer (S_1), designer (S_2), PC manufacturer (S_3), transportation company (S_4), contractor (S_5), and engineering supervisor (S_6). The project developer is the Shenzhen Housing and Project Management Station, which has undertaken a series of campus development and expansion projects in Shenzhen. The designer is the Architectural Design and Research Institute of HIT, which has a design unit rank of Class A. In China, design units are grouped into three classes (i.e., Class A, Class B, and Class C) according to the human resource, registered capital, working experience, and reputation of each unit. Design companies in Class A are the best design units in China. The PC manufacturer, a construction component company located in Dongguan, has a close relationship with the project contractor. The transportation company is a local company with extensive experience in transporting PCs. The contractor is China Construction Fourth Engineering Division Corporation Limited, which has undertaken many OCPs in China. The engineering supervisor in this project is Shenzhen Cobo Engineering Consultant Corporation Limited. These six stakeholders can all affect the ultimate quality performance of this project.

4.2. Data collection

Due to the lack of any database pertaining to OCPs, we collected the data for this case study via semi-structured interviews with key members of the six stakeholder groups, which is consistent with the approach taken in studies conducted by Ding and Xu (2018) and Neumeier et al. (2018). The interviewee selection criteria stipulated that the interviewees have a senior position or play an important role in the project (Yu et al., 2017). A total of 12 managers or engineers were interviewed to establish the structure of the Bayesian network and evaluate the probabilities of the node states.

The interview comprised three sections, i.e., node identification, edge identification, and probability evaluation. As in the study conducted by Su et al. (2016a), four types of quality defects were analyzed, including design defects (QD_1), quality defects of PCs during the manufacturing stage (QD_2), quality defects of PCs during transportation (QD_3), and quality defects of the project during onsite assembly and construction (QD_4). Quality defects at different project stages typically occurred due to different stakeholderrelated factors. The interview questions in the first section focused on identifying stakeholder-related factors that affected the occurrence of the four types of defects. The interview questions in the second section focused on the identification of the four types of edges shown in Fig. 2. The interview questions in the third section addressed the probability of node states in the Bayesian network (i.e., compiling CPTs for the network nodes) with the help of a probability scale. The scale used for probability evaluation (in Table 3) has been widely used by scholars studying construction project management, e.g., Ding and Xu (2018). This scale can help increase the accuracy of probability evaluation.

Table 3

Scale for the probability evaluation of Bayesian network.

Level of probability	Probability of occurrence	Description
1	[0, 0.0003)	It is almost impossible to occur
2	[0.0003, 0.003)	It is unlikely to occur
3	[0.003, 0.03)	It occurs occasionally
4	[0.03, 0.3)	It is possible to occur
5	[0.3, 1]	It occurs frequently

The key questions answered by the 12 interviewees during the data collection are listed in the supplementary materials (SM1, SM2, and SM3). Open-ended questions and closed-end questions were designed for different research objectives. Open-ended questions (i.e., questions 1e6 in SM1) aimed to explore new factors that were not identified by previous studies but could affect the quality performance of this OCP. Closed-end questions aimed to identify factors that were proposed by previous studies and had a close linkage with this project (questions 7e10 in SM1), and evaluate the structure (questions 1e2 in SM2) and probability distribution (questions 1e4 in SM3) of the Bayesian network. Since the tacit knowledge of interviewees was difficult to acquire, the mixed use of open-ended and closed-end questions could improve the effectiveness and robustness of the data collection.

4.3. Bayesian-network-based model in the project

The collected data (i.e., nodes, edges, and CPTs) were analyzed using the software package GeNIE (academic version). Fig. 3 shows the structure of the Bayesian-network-based model, which consists of 23 nodes, including four types of quality defects, 18 stakeholder-related factors that could incur quality defects, and the overall quality objective of this project (i.e., passing the final quality acceptance test). In Fig. 3, the ovals denote the quality defects and quality objective of this project, rectangles represent stakeholder-related factors, and arrows reflect causal relationships among different nodes. One can see that all of the identified quality defects and stakeholder-related factors can directly or indirectly affect the results of the final quality acceptance test.

4.4. Results of the case study

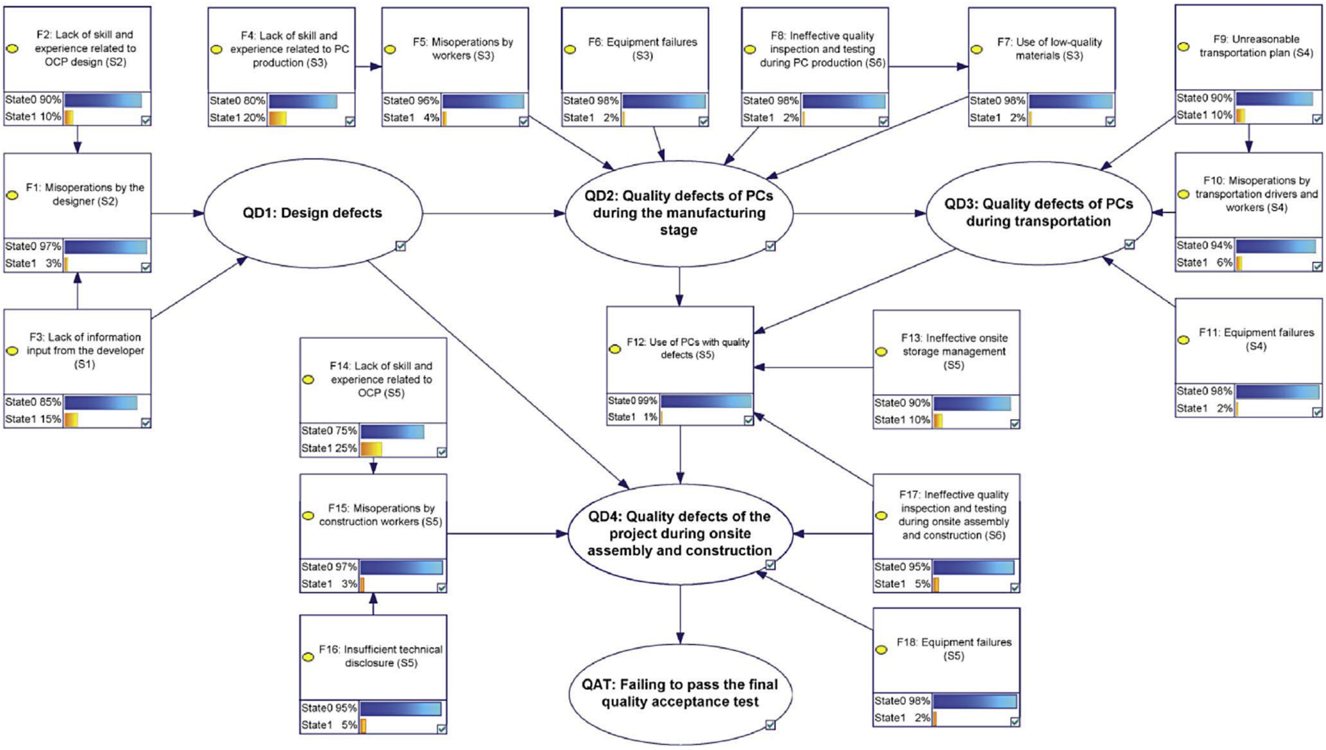
F2: Lack of skill and experience related to OCP design (S2)
State0 90%
State1 10%
F4: Lack of skill and experience related to PC production (S3)
State0 80%
State1 20%
F5: Misoperations by workers (S3)
State0 96%
State1 4%
F6: Equipment failures (S3)
State0 98%
State1 2%
F8: Ineffective quality inspection and testing during PC production (S6)
State0 98%
State1 2%
F7: Use of low-quality materials (S3)
State0 98%
State1 2%
F9: Unreasonable transportation plan (S4)
State0 90%
State1 10%
F1: Misoperations by the designer (S2)
State0 97%
State1 3%
QD1: Design defects
QD2: Quality defects of PCs during the manufacturing stage
QD3: Quality defects of PCs during transportation
F10: Misoperations by transportation drivers and workers (S4)
State0 94%
State1 6%
F3: Lack of information input from the developer (S1)
State0 85%
State1 15%
F12: Use of PCs with quality defects (S5)
State0 99%
State1 1%
F13: Ineffective onsite storage management (S5)
State0 90%
State1 10%
F11: Equipment failures (S4)
State0 98%
State1 2%
F14: Lack of skill and experience related to OCP (S5)
State0 75%
State1 25%
F15: Misoperations by construction workers (S5)
State0 97%
State1 3%
QD4: Quality defects of the project during onsite assembly and construction
F17: Ineffective quality inspection and testing during onsite assembly and construction (S6)
State0 95%
State1 5%
F16: Insufficient technical disclosure (S5)
State0 95%
State1 5%
QAT: Failing to pass the final quality acceptance test
F18: Equipment failures (S5)
State0 98%
State1 2%

Fig. 3. Interdependencies among stakeholder-related factors and quality defects in the case study.

In this section, we present evaluations of different stakeholder impacts on the quality performance of this project based on Eqs. (1)e(4). First, using Eq. (2), the impacts of different stakeholderrelated factors on the final performance of this project (i.e., the quality acceptance test) were assessed and ranked, as shown in Table 4. As a result, use of PCs with quality defects (F_{12}), misoperations by construction workers (F_{15}), ineffective quality inspection and testing during onsite assembly and construction (F_{17}) (degree of impact > 0.002) were identified as critical factors that would significantly affect the quality performance of this project. Project managers, engineers, and corresponding stakeholders should therefore pay sufficient attention to these factors.

Table 4

Ranking of stakeholder-related factors based on their impacts.

Ranking	Factor	Degree of impact	Ranking	Factor	Degree of impact
1	F_{12}	0.00273*	10	F_5	0.000188
2	F_{17}	0.00230*	11	F_{16}	0.000178
3	F_{15}	0.00223*	12	F_{10}	0.000177
4	F_3	0.00186	13	F_9	0.000156
5	F_{18}	0.00150	14	F_4	0.000121
6	F_1	0.00128	15	F_6	0.0000865
7	F_{13}	0.000958	16	F_{11}	0.0000842
8	F_{14}	0.000626	17	F_7	0.0000799
9	F_2	0.000205	18	F_8	0.0000186

Note: factors with "*" are identified as critical factors in this table.

Next, the impacts of the six stakeholder groups on quality defects and quality acceptance testing were evaluated using Eqs. (3) and (4). A relative importance indicator was used to reflect the impact of a given stakeholder group. Table 5 presents the evaluation results. Note that "-" indicates that this stakeholder did not affect the occurrence of a given quality defect. For example, in the second column of line 5, "-" is used to denote that PC manufacturer S_3 did not affect the development of the design schemes. Based on the evaluation results, one can see that the contractor (S_5) played the most important role in determining the quality performance of this project. In addition, the developer (S_1), designer (S_2), and engineering supervisor (S_6) also had significant impacts on the final quality acceptance test (level of impact > 10%).

Finally, a sensitivity analysis was conducted to identify sensitive nodes in the Bayesian-network-based model, the results of which are shown in Fig. 4. Nodes with a relatively high level of sensitivity are marked in a dark color. Factors F_1, F_3, F_{12}, F_{15}, F_{17}, and F_{18} were identified as sensitive stakeholder-related factors. Based on the aforementioned impact analysis (Table 4), F_{12}, F_{15}, F_{17} were marked as critical factors because each of them had a relatively high degree of impact on the occurrence of quality defects. In Fig. 4, all of these three critical factors have a high level of sensitivity, which confirms the importance of these factors. Although F_1, F_3, and F_{18} also had a relatively high level of sensitivity in this project, these factors were not identified as critical factors because they did not have a high degree of impact on quality defects. Quality defects at the design stage (QD_1) and the onsite assembly and construction stage (QD_4) were identified as sensitive quality defects that significantly affect the final results of the quality acceptance test. In defect control, these two sensitive defects should be given sufficient attention in light of their significant effect on the overall quality performance of the project.

4.5. Validation

Table 5

Impacts of stakeholders on defect occurrence and quality acceptance test.

In the case study, F_{12}, F_{15}, and F_{17} were highlighted as critical stakeholder-related factors that can significantly affect the occurrence of quality defects. All of these factors were also identified as sensitive nodes, which indicates that the sensitivity analysis supported the importance of these factors. In addition, F_1, F_3,and F_{18} were also identified as sensitive factors. QD_1 and QD_4 were identified as sensitive quality defects. In Fig. 3, one can see that F_1 and F_3 are linked with QD_1, and F_{12}, F_{15}, F_{17}, and F_{18} are linked with QD_4. In other words, the identified sensitive factors had close linkages with the two sensitive quality defects. Based on the impact evaluation in Table 5, stakeholders S_1, S_2, S_5, and S_6 were identified as the most important. In Fig. 3, one can see that all the critical factors and sensitive factors were controlled or affected by these four critical stakeholders. In summary, there was a high degree of consistency in the identification of critical factors, sensitive factors, sensitive defects, and critical stakeholders, which confirms the robustness and effectiveness of the data analysis.

After testing the consistency of the data analysis, the evaluation results were sent to the 12 interviewees who were asked to judge whether the evaluation results were acceptable or not. As shown in Fig. 5, the majority of the feedback from these interviewees supported the findings of this study. Furthermore, to examine the effectiveness of the Bayesian-network-based model, the interviewees were asked for the reasons for their judgments. In the following discussion section, we summarize the viewpoints of the interviewees and address the implications of the stakeholder rankings. We note that the findings of this study should be further tested in a large data sample. Similar to the studies conducted by Ding and Xu (2018) and Neumeier et al. (2018), a case study was used to illustrate the application of the model, but its results cannot confirm that the conclusions of this study are applicable to other cases.

5. Discussion

5.1. Ranking of stakeholder impacts in the case study

In terms of controlling quality defects in OCPs, the importance of the contractor has been highlighted by researchers such as Su et al. (2016b) and Arif et al. (2012). The results of this case study were consistent with the findings of these researchers. The project manager of the contractor stated that the use of offsite construction had significantly changed the way they worked. Since the scope of the work, project management mode, and workflows of OCPs differ from those of in-situ construction projects, they presented significant challenges to the contractor. For example, to facilitate onsite assembly, the contractor had to use advanced information equipment such as RFID, mobile devices, and a smart construction platform, which were previously unfamiliar to them. Due to these changes, the contractor had to bear a relatively high level of risk with respect to quality and this played an important role in the

Stakeholder	Relative importance of S_i in terms of impacting				
	(QD$_1$)	(QD$_2$)	transportation (QD$_3$)	construction (QD$_4$)	acceptance test
Developer (S$_1$)	55.68%	8.84%	4.98%	12.60%	12.60%
Designer (S$_2$)	44.32%	7.04%	3.96%	10.03%	10.03%
PC manufacturer (S$_3$)	e	80.96%	45.61%	3.22%	3.22%
Transportation company (S$_4$)	e	e	43.67%	2.83%	2.83%
Contractor (S$_5$)	e	e	e	55.65%	55.65%
Engineering supervisor (S$_6$)	e	3.16%	1.78%	12.60%	12.60%

Design defects Quality defects of PCs Quality defects during Quality defects during onsite assembly and Quality

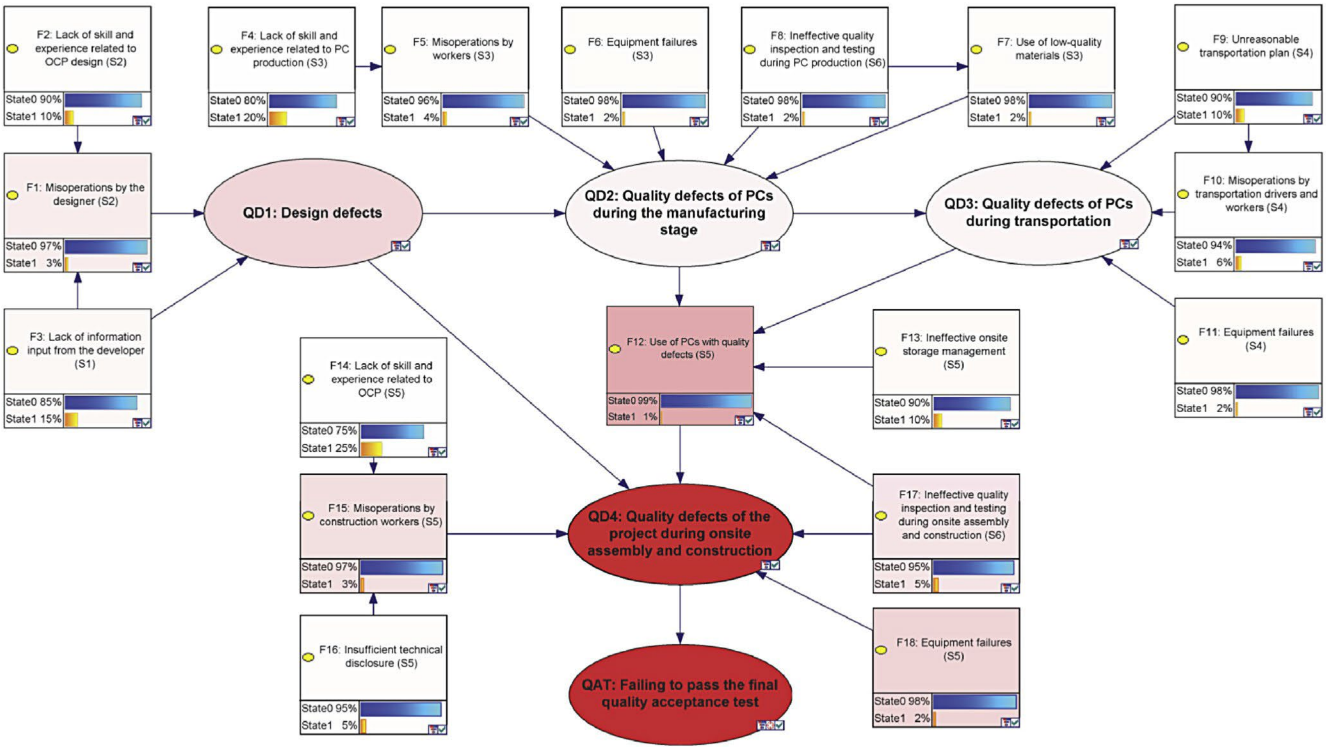

Fig. 4. Sensitivity analysis of the case study.

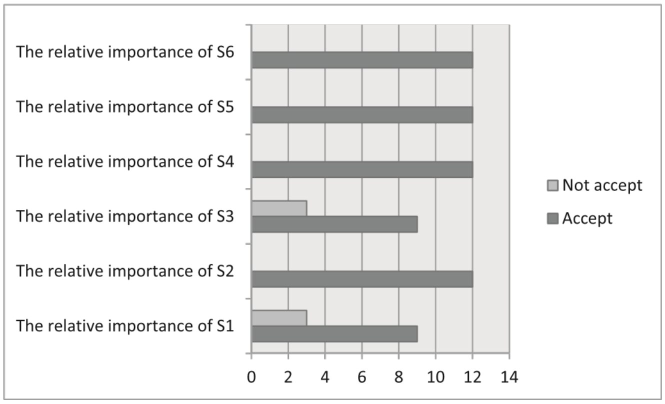

Fig. 5. Feedback of interviewees regarding the evaluation on stakeholder impacts.

mitigation of defects. Accordingly, the contractor significantly affected the quality performance of the OC.

The designer, developer, and engineering supervisor also played significant roles in quality management. To facilitate PC production and onsite assembly, the design scheme must be reasonable, accurate, and detailed. A slight error in the design scheme (e.g., deviations in the bolt positions) could significantly affect the accuracy of onsite assembly. Therefore, the designer can significantly influence the performance quality of this project. The design of the OCP in this study was based on the requirements of the developer. If the design scheme failed to meet the demands of the developer, then reworking might be required. Therefore, the developer's input was critical for avoiding design defects. Although the developer had already undertaken a few campus extension projects in Shenzhen, the primary business of the developer been housing projects. Due to the developer's relatively limited experience and knowledge regarding campus extension, to mitigate design defects, he had to exert sufficient effort to effectively communicate with the designer. In addition to the designer and developer, the engineering supervisor also had a relatively high level of impact on the final quality of this project. In this case, the engineering supervisor was responsible for the inspection and identification of defects. This OCP involved a series of production and construction activities that were closely linked. Thus, it was important to accurately identify quality defects in each critical activity since a defect in one activity could significantly affect those that followed. Therefore, the inspection and identification of defects was a critical aspect of this project, which means the supervisor played an important role in quality management.

In the case study, the PC manufacturer had a relatively low impact on the final quality of the project, which is inconsistent with the findings of previous studies such as Cao et al. (2018). The main reason for this is that the probability of using low-quality PCs for onsite assembly was very low. First, the PCs were manufactured at an industrialized factory where there is strict quality control on the production line. As such, quality risk factors like intense temperature changes, unstable pH values, and fluctuations in humidity are effectively mitigated. In addition, strict offsite and onsite quality inspections were performed by the project's engineering supervisor. Before the PCs were shipped from the factory, the engineering supervisor assigned staff to visit the production site and test the quality performance of the PCs, and those with any quality defects were not transported to the construction site. When the approved PCs arrived at the construction site, the engineering supervisor rechecked the quality of each PC and sent any unsatisfactory PCs back to the factory for reworking. Therefore, the probability of using lowquality PCs during onsite assembly was kept to a minimum. As such, the manufacturer's impact on quality defects was effectively controlled in this project.

The transportation company was responsible for transporting PCs from the factory to the construction site. Due to the limited nature of this work in relation to the overall project, the transportation company did not have a high level of impact on the project quality. In addition, during the transportation process, RFID, GPS, and video monitoring technologies were used to track PC quality. As a result, among the six stakeholders, the transportation company played the least important role in defect management.

5.2. Theoretical and practical implications of this study

The results of this study contribute to the fields of quality defect analysis and stakeholder evaluation. Compared to other studies that have focused on the identification of factors that incur quality defects in OCPs (e.g., Zheng et al., 2016; Su et al., 2016a; Qi et al., 2016), in this study, we analyzed the interdependencies of these factors using a Bayesian network, and then we quantified the importance of the different factors by Bayesian analysis. In previous studies, the importance of a factor was typically measured based on its direct impact on the occurrence of quality defect (e.g., Gan et al., 2017). In this study, the degree of importance of each factor was assessed using a network-based perspective, which integrates the direct and indirect impacts of factors in the importance evaluation.

According to Arashpour et al. (2016), interactions between offsite and onsite activities are characterized by uncertainties. Previous studies evaluating factor importance have not investigated the impacts of project uncertainties. For example, in the study conducted by Gan et al. (2017), the mean values of an importance assessment questionnaire were directly used to rank the relative significance of quality factors. Indicators that could reflect uncertainties (e.g., standard deviation) have not been considered in studies of this type. In this study, we used a Bayesian-networkbased model to analyze the occurrence of defects in uncertain environments, and we considered the impacts of project uncertainties in the process of evaluating factor importance.

In addition, this study bridges the areas of quality and stakeholder management. In fields related to the quality management of OCPs, studies (e.g., Cao et al., 2018; Yu, 2017) have typically focused on research questions like: “What factors are important for quality management?” and “How can practitioners improve their quality management practices?”. In contrast, this study addressed the following questions: “Who are the important players in quality management?” and “Who should have responsibility for mitigating quality defects?” As the performance of OCPs relies heavily on stakeholder collaboration (Xue et al., 2018), sufficient attention must be given to critical stakeholders when developing the quality management plan.

Finally, the results of this study can be used to improve the stakeholder evaluation process. Traditional methods for stakeholder impact evaluation (e.g., Olander, 2007; Li et al., 2018b) generally focus on the inherent attributes of stakeholders. By linking stakeholders with factors that affect the occurrence of defects, in this study, we measured stakeholder impacts based on the dependencies among stakeholders.

Practically speaking, the findings of this study can help practitioners to better control quality defects in OCPs. First, we summarized stakeholder-related factors that may lead to quality defects in OCPs based on a literature review and case study (see Table 1 and Fig. 3). These factors can be used as a checklist by project managers and stakeholders to identify the potential risks of defects. A comprehensive identification of quality risks can help practitioners design quality management plans and reduce the probability of the need to rework. Second, we confirmed the effectiveness of the Bayesian-network-based method for evaluating the relative importance of stakeholder-related factors with respect to defect occurrence. Practitioners can focus on these most critical factors and thus be more efficient and effective in defect mitigation. Third, the impacts of different stakeholders on each quality defect can be evaluated using the proposed model, which also provides a reference for the division of stakeholder responsibility regarding quality. Thus, project managers can focus on critical stakeholders that have a high level of impact on quality defects. These critical stakeholders can then be encouraged to improve their quality management. Fourth, the Bayesian-network-based model can be used to predict the final quality performance of OCPs. Project managers can utilize this model to assess the quality performance of different project implementation schemes. Thus, at the OCP planning stage, an effective project implementation scheme can be selected.

6. Conclusion

In this study, we used a Bayesian network to evaluate stakeholder impacts on the occurrence of quality defects in OCPs, with consideration given to the dependencies among stakeholders. To investigate the occurrence of quality defects in OCPs, we developed a Bayesian-network-based model, in which the defects and stakeholder-related factors that could incur these defects were explored using Bayesian analysis. The proposed model was then used to effectively evaluate stakeholder impacts on defect occurrence. The evaluation results enabled the identification of critical stakeholders and stakeholder-related factors. In a case study demonstrating the application of the evaluation model, use of precast components with quality defects, misoperations by construction workers, and ineffective quality inspection and testing during onsite assembly and construction were identified as the most important factors affecting quality defect control. Additionally, we found the contractor to have the highest level of impact on the occurrence of quality defects. We expect that the findings of this study contribute to the body of knowledge regarding quality defect management and stakeholder impact evaluation.

A few limitations must be acknowledged. First, the main findings of this study have not been validated in a large data sample. In future studies, OCPs with different conditions should be investigated to further test the effectiveness of the Bayesian-networkbased model, and to identify any necessary modifications that would improve its performance. Second, due to the lack of any OCP database, the parameters used in the case study were assessed based on the knowledge of key project participants, which is similar to the approach used by Ding and Xu (2018) and Neumeier et al. (2018). Therefore, the data collection process may reflect the subjective biases of the interviewees. In future studies, a database pertaining to OCPs should be established to enable practitioners to evaluate OCP project parameters by big data analysis.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.118390.

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