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Quantifying and visualizing value exchanges in building information modeling (BIM) projects

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ABSTRACT

This study presents a novel method based on stakeholder value network (SVN) to quantify and visualize value exchanges among primary stakeholders when using the building information modeling (BIM). After collecting data from 135 BIM experts from various capital projects in the mainland of China, 95 value flows among 7 BIM-related stakeholders were quantified, including 69% intangible value and 31% tangible value flows. Owners were then selected as focal organizations to analyze 49,775 value cycles starting from and ending with owners. 9 top-ranked value cycles, 3 most important stakeholders (BIM consultants, general contractors, and sub-contractors), and 20 top value flows were identified and discussed to enable owners to formulate effective strategies to drive BIM value realization. These results can provide a visualized tool to quantify the perceived value of BIM stakeholders and to formulate value-based strategies to encourage the "buy-in" decisions by stakeholders.

1. Introduction

Building information modeling (BIM) is a promising technology used within the architecture, engineering, and construction (AEC) industry to design, construct, and maintain buildings [1]. It has been defined as "a set of interacting policies, processes, and technologies generating a methodology to manage the essential building design and project data in digital format throughout the building's life-cycle" [2]. Since it was first proposed in the 1970s, a number of BIM tools and applications have been developed to improve the effectiveness of architecture, design, construction, operation, and use for the built environment [3]. BIM can be a powerful tool for improving design quality [4,5], construction safety [6] and productivity [7], boosting management efficiency [8] and reducing construction costs and delays to ultimately support more favorable outcomes for end users [9–11]. Communication among project stakeholders has also been altered by the introduction of BIM in the AEC industry, where BIM is used to facilitate the sharing of information, knowledge, and technology among multiple stakeholders throughout a project's lifecycle [12].

Values are regarded as subjectively desirable outcomes of project stakeholders. Although the potential value of BIM may appear self-evident, the AEC industry has been slow to accept BIM implementations for three main reasons [13,14]. The first is that in spite of the evidence, stakeholders lack both an appreciation of and quantifiable evidence for the value added by BIM. Although the perceived value should be a clear motivator for organizations in the AEC industry to adopt new technologies [15], the justification for owners' investment in BIM has been primarily based upon the return on investment (ROI), which merely considers tangible values without incorporating intangible ones. This is important because contractors, especially mid-sized ones, will hesitate to adopt BIM unless the owners demand it [16].

Secondly, most of the research on this topic has focused on implementations within a single organization in the construction supply chain, ignoring the value creation across the entire supply chain. This makes it difficult to compare the perceived values and reward sharing across different stakeholders. For instance, designers use BIM to enhance drawing quality and design coordination, while contractors focus on improving project productivity, scheduling, and safety based on BIM models [17]. Although designers strive to utilize BIM in the early stage, it may turn out to create more values for contractors instead of themselves received. It is therefore necessary to evaluate and compare the perceived values among different BIM stakeholders so as to thoroughly

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Table 1
Notations used in the SVN model.

Concept	Legend	Definition
Node	A	Stakeholder
Link/Value flow	$A \xrightarrow{S\#} B$ OR $A \rightarrow S\# \rightarrow B$	The specific needs of a stakeholder (B), received from another stakeholder.
Value path/Value exchange	$A \xrightarrow{S\#} B \xrightarrow{S\#} \cdots \xrightarrow{S\#} X$ OR $A \rightarrow S\# \rightarrow B \rightarrow S\# \rightarrow \cdots \rightarrow S\# \rightarrow X$	A string of value flows connecting a group of stakeholders. When X = A, it is a value cycle.
Value cycle	$A \xrightarrow{S\#} B \xrightarrow{S\#} \cdots \xrightarrow{S\#} A$ OR $A \rightarrow S\# \rightarrow B \rightarrow S\# \rightarrow \cdots \rightarrow S\# \rightarrow A$ OR $A \rightarrow A$	Value paths beginning from, and ending with, the focal organization.

understand the value trade-offs inherent in BIM use and allocate the rewards and incentives more accurately, especially in new collaborative arrangements such as integrated project delivery (IPD).

The third reason why the AEC industry has been slow to adopt BIM implementations is that although some attention has been paid to identifying BIM's potential benefits for organizations, researchers have generally neglected the value exchange and interaction process through which stakeholders realize these expected benefits. In this study, we therefore focused on value flow, which is defined as the specific needs of a stakeholder that are met by another stakeholder (Table 1), specifically the process of value delivery across stakeholders. As yet, the interactions of stakeholders in BIM-based projects have not been clearly analyzed. Construction projects consist of a series of non-linear, complex, iterative, and interactive processes, so it is necessary to analyze the impact of stakeholders' interactions from a network perspective [18–20]. There is thus a need to develop a quantitative method to systematically evaluate the perceived value for key multi-stakeholders and their multi-type interactions in order to provide concerted strategies for promoting value delivery across the stakeholder network.

In the current literature, an increasing number of scholars are now using quantitative methods such as social network analysis (SNA) to extend the research focus from an individual BIM stakeholder to an overarching network theory that includes multiple stakeholders [18]. However, most researchers have only considered a single type of relationship within a network and are thus unable to capture multiple types of relationships (e.g. financial, information, services) in the same network in order to accurately evaluate the perceived values of stakeholders. Furthermore, current methods focus on the direct relationships and the network structure, ignoring the indirect relationships among multiple stakeholders that are essential if researchers are to be able to identify and evaluate critical value flows and circles for value delivery in a BIM-use network [21].

In this respect, a multidisciplinary approach known as stakeholder value network (SVN) analysis provides a systematic lens through which to examine, understand, model, and manage multi-type stakeholder relationships, thereby illustrating the applicability of a network approach for realizing BIM value in construction projects. By viewing a BIM implementation as a multi-relational inter-linkage of stakeholders in a construction project, this study utilizes an SVN model to reveal the value flows and driving paths of BIM implementations among project stakeholders, with the ultimate objective being to facilitate future BIM applications and developments. This study has three specific objectives:

(1) To construct a quantitative network-based SVN model for BIM-based construction projects that considers inter-organizational collaborations and value exchanges;
(2) To identify the important value cycles, stakeholders, and value flows for BIM implementations based on the proposed SVN model; and
(3) To provide effective strategies for stakeholders that drive widespread BIM implementations.

The remainder of this paper is structured as follows. The following section reviews the literature related to the value of BIM and its stakeholder network. The application, assumptions, and methodology of the SVN method are then introduced in Section 3. The research method applied for the study's SVN analysis of BIM implementation is presented in Section 4, including both qualitative and quantitative models, value cycle searching, and the calculation. Section 5 reports the results for the whole network, while Section 6 examines the value cycles, stakeholders, value flows, and strategies from the owners' perspectives. Finally, Section 7 concludes with a summary of the study and discusses its contributions, limitations, and possible directions for future research.

2. Literature review

The solutions and work processes involved in a BIM implementation are not yet firmly established, mainly because the value of BIM has not yet been clearly articulated [22]. However, a number of scholars have investigated the challenges related to BIM value realization and sought to determine the best way to quantify BIM values and conduct value analyses using network-based approaches; these are reviewed in this section.

2.1. BIM and value realization

BIM is applied as a process to create value based on the multi-relational collaborations of stakeholders [23]. However, two main barriers hamper efforts to realize the full potential of BIM, the most important of which is that BIM functions are not fully integrated across different parts of a project. Although BIM can be utilized in nearly all of the processes involved in a construction project, the majority of firms merely adopt partial BIM functions, and thus only subsets of values have been explored [24]. Scholars have advocated promoting a more comprehensive use of BIM that goes beyond simply detecting clashes in field installations [25]. Although BIM is intended to connect different stakeholders and support their interdependent work processes, closer collaborations across different organizations are seldom, if ever, encouraged [26]. This means that although the BIM adoption rate in the U.S. has climbed to almost 70% [27], BIM implementations are often performed separately by the various stakeholders involved in the design and construction processes [28]. Companies are beginning to appreciate the importance of fully realizing the potential value of BIM, however, and more firms are collecting BIM inputs from all players early in the design process in order to support greater collaboration, making it possible to implement BIM to improve processes beyond their own firms [29]. Unfortunately, if a designer does not consider a contractor's requirements, or vice versa, the implementation of BIM in a design or construction organization can actually be counterproductive due to the inherent interdependencies in construction projects. This means that intensive interdependence and close collaborations among key stakeholders are required to achieve the full potential of a BIM implementation.

The second major barrier is the lack of a widely accepted method to measure the interrelated values of BIM among stakeholders. These values cannot be measured without a full understanding of how the business values from investment can be shown, and although all project stakeholders may appreciate how they themselves can benefit from the application of BIM, they seldom see the big picture. Existing research in this area has mainly investigated the value gained by specific types of stakeholders such as owners [30], designers [31], and contractors [19]; the synergies to be gained by multiple stakeholders working together has yet to be explored. Dehlin and Olofsson [32] have therefore argued that the focus must shift from studying the benefits gained by individual stakeholders to studying the effect on the project as a whole, which would provide additional support for better coordination between stakeholders by optimizing the use of BIM within the AEC area.

2.2. BIM and value measurement

Many studies have sought to gain a better understanding of the value of BIM in construction projects. In terms of the values derived from BIM utilization, these fall into two main categories: 1) those that determine appropriate metrics with which to measure BIM values for individual stakeholders [23,33], and 2) those that develop an applicable framework or process to assess values and to guide BIM best practices [19,30].

The research methods utilized by these studies include surveys [34], case studies [35], individual analyses, and theoretical treatments [33,36]. Among these, case studies are most commonly used and include reports of successful BIM implementations with their quantitative savings [23,37] and cross-case comparisons to assess improvements in project performance achieved using BIM [8,29,38].

Several researchers have attempted to quantify the purported value of using BIM during the construction phase [32,39]. However, the data used in these studies relies heavily on anecdotal evidence, and their results can be subject to large variances: Azhar et al. [9], for example, presented a range for ROI of somewhere between 140% and 39,900%. These huge variations are mainly due to the different benefit realization mechanisms utilized, but also to a lack of tools that are capable of quantifying intangible values. Being aware of this deficiency, Azhar et al. [41] went on to use comparative case studies to examine the various tangible and intangible values achieved by all stakeholders through implementing BIM. However, although many studies have discussed the intangible values, none have yet considered the value interactions among different stakeholders.

2.3. BIM and network-based analysis

BIM is a complex, system-wide innovation, and it has been suggested that it can be extended to encompass networks of organizations that are linked to each other [25]. Therefore, scholars have recently expanded their focus from individual organizations to network theory and relevant methods, highlighting the relationships and interactions among organizations [42]. Networks within the construction industry take the form of reciprocal relationships that involve giving and receiving mutually supportive services within a project network [23,43]. Adopting a network perspective that focuses on the interactions between organizations requires different strategies [44].

Several network-based methods have been employed for BIM implementations. For example, a benefit dependency network has been proposed as a benefit management approach to determine who is accountable for making specific changes and delivering benefits [45], while actor-network theory (ANT) has been used to examine the development of a network of actors in order to address the adoption of information and communication technology (ICT) [25,40,46]. Another popular network-based method is social network analysis (SNA), which has been employed to reveal the potential of BIM in relation to improving inter-organizational communication and understanding the process of design management in BIM-based projects [46,47]. An analysis of the roles and relationships of actors in these networks provides important knowledge about their potential motivations to determine their own interests and roles in a network. However, current network methods suffer from two important limitations. First, they mainly consider a single type of connection/relationship in a network such as SNA, and are thus incapable of capturing the many different types of relationships (e.g. financial, information, services) that are an integral part of real world networks. As a consequence, the complexity of multilateral and multi-type relationships among stakeholders cannot be analyzed. Second, other methods like ANT primarily focus on mapping various relationships through qualitative empirical case studies, but they are unable to quantify value delivery among multiple stakeholders, including both direct and indirect, tangible and intangible values of BIM.

When BIM has been employed to improve inter-organizational collaboration, this inevitably involves multiple stakeholders with different perceived values. This means that an inclusive approach is required to define the interests of each stakeholder and to evaluate the perceived values of each based on their expected benefits from the collaboration. Such a requirement has also been identified by the ICT sector, where it has been acknowledged that ICT research should not only analyze the value impact but also its capacity to act as a “bridge” for flows across the value network from an inter-organizational perspective [48]. In this respect, it is essential to develop a systematic method that can be used to understand and quantify the delivered values among key stakeholders in BIM implementations.

3. Stakeholder value networks

Stakeholder Value Network (SVN) is a network-based multidisciplinary approach used in stakeholder analyses to analyze the value delivery mechanisms. Based on social exchange theory (SET), SVN analysis represents a qualitative/quantitative network approach [49] that is capable of computing both direct and indirect stakeholder influences. An SVN model incorporates a focal organization, its stakeholders, and all the value exchanges between the focal organization and stakeholders, as well as those between the stakeholders themselves. In this context, the focal organization is defined as the stakeholder selected as the spotlight for the analysis.

A BIM value analysis requires a thorough investigation of the intersectional and multi-type relationships related to value creation and value delivery among the stakeholders. Compared with other network-based methods (such as SNA that examines a single type of relationship in the network analysis), SVN integrates the impacts of multi-type relationships (e.g. social and economic, tangible and intangible) within the same network by using subjective utility analysis. Current methods also tend to focus on dyadic ties and the network structure rather than the generalized value exchanges related to the indirect relationships among multiple stakeholders that are essential to identify and evaluate critical value flows and circles, thus promoting value delivery in the stakeholder network [21].

In this regard, the SVN method innovatively contributes to modeling multiple types of relationships in a BIM-use network. This makes it a useful way to model, quantify, analyze, and understand the value transactions and delivery between stakeholders in BIM-based projects from the perspective of the network (hereinafter referred to BIM-SVN), thereby supporting the development of explicit strategies to maximize their potential benefit from BIM.

3.1. Theory and assumptions

In SVN analyses, three key assumptions originating from SET provide theoretical support for this analysis of BIM implementation in construction projects. Social exchanges are an extension of economic exchanges, so the first of these assumptions is that social and economic relationships can be combined in a common framework. All stakeholder relationships can be evaluated by a subjective utility analysis. In BIM-based projects, contractual relationships represent economic relationships while collaborative relationships represent social relationships, so both these relationships are taken into account in a BIM-SVN analysis.

The second assumption is that the exchange patterns in SVN can be divided into restricted (dyadic or bilateral) and generalized exchanges [50], with the former signifying a direct relationship between any two stakeholders and the latter the impact of indirect relationships among multiple stakeholders. As multilateral and indirect value exchanges among stakeholders are common in BIM collaborations, generalized exchanges are regarded as the most fundamental form of value exchange in the BIM-SVN model, supplemented by restricted exchanges.

The third assumption is that the stakeholders adopting BIM are aware of the value derived from the value delivery system and of its delivery mechanism for the sustainable use of BIM. Although an understanding of BIM's value is still somewhat limited in the construction field [64], for this study professionals who were already aware of BIM values were recruited in order to develop and quantify the BIM-SVN model. This allowed investigators to develop network statistics that measure the value perceived by each stakeholder and thus carry out a targeted strategy analysis [49].

3.2. SVN analysis method

The SVN analysis method involves four major steps – mapping, quantifying, searching, and analyzing – to determine value creation and delivery among stakeholders [51]. The specific methods involved in each step are introduced in turn below.

3.2.1. Mapping qualitative model

An SVN model consists of two components, nodes and links, denoting the stakeholders and value flows, respectively (see Table 1). It is essential to develop a complete list of stakeholders and to identify the value flows between each pair of stakeholders.

The first step is to identify the stakeholders in order to shape the network boundaries and scopes within the SVN analysis. Two kinds of stakeholders are considered in this study, namely internal stakeholders who are actively involved in the execution of the project and key external stakeholders who are affected by the project [52], such as government agencies.

The next step is to identify the value flows between each pair of stakeholders [53]. In this study, values are regarded as subjectively desirable outcomes created by a sender that they then pass on to a recipient in the project. In order to define value flows, the approach of "stakeholder characterization templates (SCT, see Appendix D)," proposed by Sutherland [54], is adopted. SCT provides a traceable, consistent, and deep understanding of how stakeholders pass resources that they own to each other and thus acquire desirable value. By employing SCT, the roles, objectives, and specific needs of each stakeholder can be identified in a stepwise manner, enabling the specific needs of each stakeholder to be mapped as value flows originating from other stakeholders [54,55]. As each input to a receiving stakeholder is identified, it becomes an output from the sending stakeholder so the sum of all the value flows can be mapped to create a complete set of value-delivering interactions within the SVN.

3.2.2. Quantitative modeling

In this step, the stakeholder maps are transformed into a quantitative BIM-SVN model by scoring the value flows according to their perceived utility for the recipient stakeholders. Each value flow is assigned a numeric score based on the level of need perceived by the recipient and the resulting scores represent the involvement of stakeholders in the active BIM implementation.

Based on previous research [21,54], two attributes can be used to describe each value flow in the SVN analysis. The first, "intensity of a need," characterizes a value flow from the demand side of the recipient stakeholder, and the second, "importance of source in fulfilling a need," characterizes a value flow from the supply side of the recipient stakeholder [49]. The more desirable it is that a source fulfills a particular need, the more important of this source it is and vice versa.

A questionnaire can be constructed to assess both attributes measured using five scales. The utility score for each value flow (U_f) is the multiplicative result of the scores of two attributes. The multiplicative function normalizes all the value flow scores within the range of [0, 1], which is consistent with the settings traditionally used in utility theory. The detailed calculation rules are provided in Appendix A.

3.2.3. Searching for value paths

A value path is a string of value flows connecting a group of stakeholders. Value paths beginning from and ending with a focal organization are regarded as value cycles, and these are utilized to construct network statistics and to measure the exchange and structural properties of the SVN. The propagation rule for value cycles requires that stakeholders and value flows can only be visited once along each value cycle, excluding the start/end stakeholder. A multiplicative rule is used to calculate the score of a value path [21]. The score of a path is equal to the product of the scores of all the value flows along that path (see Eq. (1) below) and the length of the value path is inversely proportional to the score. This multiplicative rule ensures that all the scores of the value path remain bounded within the range of [0, 1], which is again consistent with the traditional settings for utility theory. Eq. (1) is presented as

$$U_c = \prod_{n=1}^{x} U_{f(n)},\ 2 \le x \le m - 1,\ x \in Z, \tag{1}$$

where $U_{f(n)}$ denotes the score of n-th value flow in the value path, and x denotes the number of value flows in the value path. In an SVN model that includes m stakeholders, a value path may include minimal 2 and maximum m-1 value flows.

3.2.4. Analysis of results

3.2.4.1. Value cycle analysis. Once all the value cycles from the focal organization have been identified and ranked, the relative importance of these value cycles is obtained. Critical cycles with a high score can provide useful guidance to formulate strategies that will engage other stakeholders.

3.2.4.2. Stakeholder analysis. In BIM-based projects, the realization of BIM's benefits in an organization are not felt solely within the confines of the enterprise-wide IT department, but support cooperation, collaboration, and commitment across all business functions [56]. To quantify the organizational capability and its importance to other stakeholders, the concept of benefit realization capability (BRC) is introduced here to represent the competences required to organize and manage the potential benefits to be gained from a BIM implementation [30].

In this study, the BRC of stakeholders is assessed in terms of their Weighted Stakeholder Occurrence (WSO), which represents how frequently the stakeholder is involved in particular value cycles divided by all the cycle scores for the focal organization (see Eq. (2) [54]); the higher the WSO, the more benefit that stakeholder captures from the BIM implementation. If the WSO score is 1.0, this indicates that a stakeholder appears in all value cycles, showing that this stakeholder gets the maximum benefit possible through their use of BIM. WSO is a comprehensive index that contains both the utility scores of the value cycles (U_c) and the number of relevant value cycles (measured by s_{kc}), as

$$WSO_k = \frac{\sum_{c=1}^{n} U_c \times S_{kc}}{\sum_{c=1}^{n} U_c}, \tag{2}$$

where k denotes a stakeholder in the use of BIM, n denotes the total number of value cycles for the focal organization (referred to owners) in the use of BIM, U_c denotes the utility score of cycle c, and s_{kc} indicates 1 if stakeholder k is included in cycle c, or 0 when not included.

3.2.4.3. Analysis of value flow. Weighted Value Flow Occurrence (WVFO) is used to measure the relative importance of each value flow by counting the weighted occurrence of that value flow in all the value cycles of a focal organization. It is calculated as shown below in Eq. (3) [54]; a higher WVFO indicates a more important value flow. Note that WVFO takes into account the effect of both the attributes of a value flow (represented by U_c) and its structural position (measured by V_{pc}) of this value flow,

$$WVFO_p = \frac{\sum_{c=1}^{n} U_c \times V_{pc}}{\sum_{c=1}^{n} U_c}, \tag{3}$$

where p denotes a value flow for BIM use, n denotes the total number of value cycles for the focal organization (referred to owners) in the use of BIM, U_c denotes the utility score of cycle c, and V_{pc} indicates 1 if value flow p is included in cycle c, or 0 when not included.

4. Research method and preliminary model

Using SVN theory, the framework for BIM-SVN modeling shown in Fig. 1 can be constructed. The first step is to map the identified stakeholders and value flows to be included in the BIM implementation and establish a qualitative BIM-SVN model. The second step uses information from the questionnaire survey (described below in Section 4.2) to quantify the value flows in the above model. In the third step, all the value paths for a particular focal organization are searched utilizing the propagation rule and organizational interdependent matrix. Finally, the critical value cycles, BRC of stakeholders, and important flows are analyzed using network statistics.

4.1. Mapping BIM stakeholders and value flows

4.1.1. Stakeholders

The BIM stakeholders are highly related to the project characteristics (project type and project delivery system). In China, BIM-based projects are typically capital projects involving the construction of large infrastructure elements such as ports, airports, roads, highways, water supply networks, and drainage systems. These projects are predominantly funded by government agencies, and are subject to strict deadlines, quality requirements, and budgets [13], all of which are listed as priorities within the application and promotion of BIM technology [57]. This is similar to the practice in other countries, such as the United States, Finland, the United Kingdom, and Singapore [58–61]. The project delivery system also identifies the BIM stakeholders involved. In this respect, as the most prevalent delivery system used in capital projects in China, the Design-Bid-Build (DBB) method was selected for use in this study [13].

As BIM is still in its early stage in China, most capital projects utilize BIM by hiring BIM consultants who are responsible for providing various BIM-related services to the owners, such as three-dimensional presentations, clash detection, and schedule simulations [1,62]. In this context and after consulting BIM related academic publications, handbooks and white papers (i.e. [10,25,63,64],), seven categories of stakeholders were identified, including government departments and organizations (hereinafter referred to as "governments" and coded "G"); owners (coded "O"); BIM consultants (coded "BC"); designers (coded "D"); general contractors (coded "GC"); subcontractors (coded "SC"); and cost consultants (coded "CC") (Appendix B). Operators are not included here because BIM is seldom used in facility management [65,66].

4.1.2. Value flows

Document analysis has been primarily employed to define the roles, objectives, and specific needs for SCT. The related documents incorporate BIM-related peer-reviewed articles (e.g., [8,30,67,68]), technical reports of BIM applications (e.g., [63,69,70]), guidelines published by authorities and regulatory bodies (e.g., [34,71–80]), and media reports and newsletters (e.g., [62,71]) that reflect the latest BIM developments. The development of the SCTs was supported and supplemented by interviewing 16 experts (2 government officials, 3 owners, 3 BIM consultants, 2 designers, 2 contractors, 2 subcontractors, and 2 cost consultants) to adapt the content for the specific context of Chinese BIM-based projects. All the experts recruited for this exercise had at least two years of BIM experience and five years of professional experience in capital projects; 37.5% were project/team managers, 12.5% department managers and 50.0% project directors. The results of these expert interviews led to further refinement of the model, including adding five needs (value flows) and the removal of one from the preliminary SCT and rephrasing the project stakeholder's roles, objectives, special needs and inputs (value flows) to avoid confusion.

Upon completion of the preliminary SCT (shown in Fig. 2), an additional 7 BIM experts (one for each stakeholder category) were interviewed to verify the suitability and accuracy of the SCT. Their answers helped to refine and confirm the SCT for the final questionnaire (described in Section 4.2). A total of 95 value flows were identified for the seven types of stakeholders; details are provided in Appendix C. All value flows were numerically coded by "recipient" and "number of value flows," with O01 representing the first value flow associated with the owner, for example. Taking the various features of BIM-related value flows into account, four types of value flows were then categorized: financial, goods/services, knowledge/information, and policy flows. Note that when applying SET to the AEC industry, value flows can be further divided into tangible flows (financial, goods/service) and intangible flows (knowledge/information, policy), which are related to tangible value and intangible value, respectively. Tangible value is generally associated with economic or monetary exchanges of goods/services and financial resources, while intangible value tends to be associated with social or nonmonetary exchanges related to exchanges involving political support and regulatory approval or information such as technical know-how and process knowledge.

4.2. Quantifying BIM-SVN model

Once the qualitative BIM-SVN model had been constructed, a questionnaire survey was conducted to collect data with which to quantify the value flows. Since each category of stakeholder is associated with distinct value flows and a unique questionnaire was therefore required, a total of seven questionnaires were designed, one for each stakeholder category. These questionnaires consisted of two sections, the first of which was used to collect demographic information pertaining to respondents such as their work experience and qualifications. Participants were selected who had at least two years of BIM

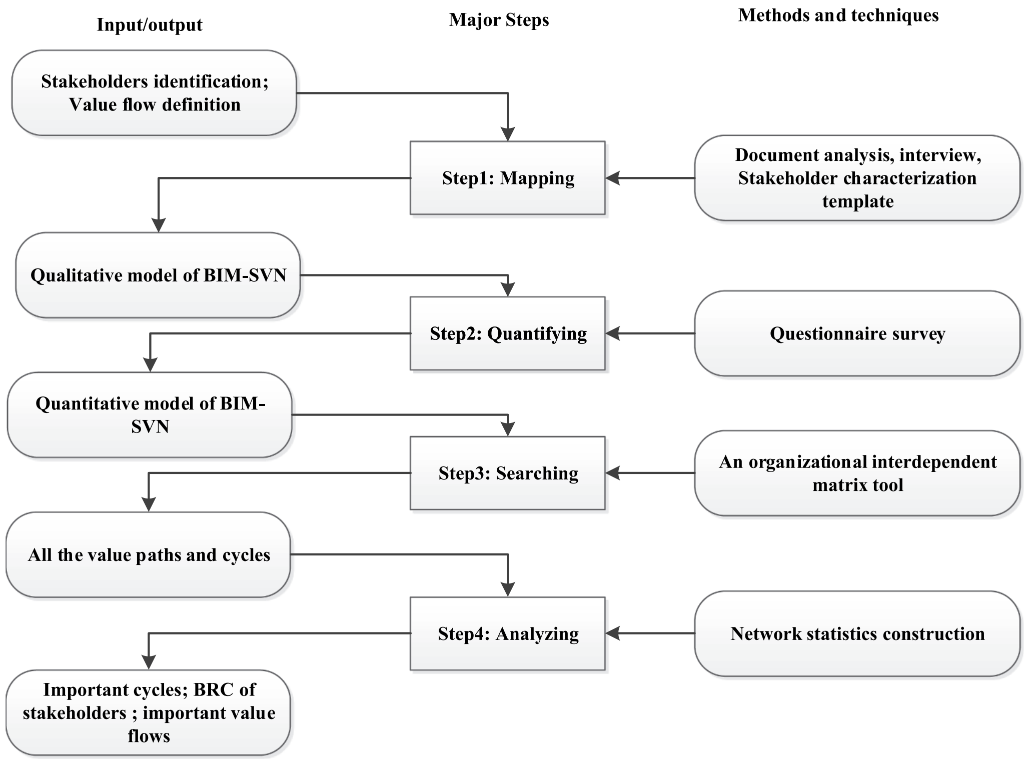

Fig. 1. Framework of the BIM-SVN modeling process.

experience and five years of professional experience in capital projects. The second section was used to assess "intensity of a need," and "importance of source in fulfilling a need" for an individual value flow. The questionnaires were distributed to organizations in four major Chinese cities (Shanghai, Beijing, Shenzhen, and Wuhan) as these cities are where the majority of BIM-based capital projects being located including, for example, the construction of the Shanghai Tower and the Wuhan metro. The surveys were conducted by email, online survey, or face-to-face interviews between July 2014 and December 2014, with 135 valid questionnaires ultimately collected from the government (7%), owners (13%), BIM consultants (18%), designers (22%), contractors (16%), subcontractors (10%), and cost consultants (13%). Once the data collection process was complete, a single utility score for each value flow was calculated based on the method given in Appendix A. The final score for each value flow was the mean score awarded by the relevant survey respondents. The quantitative BIM-SVN model was

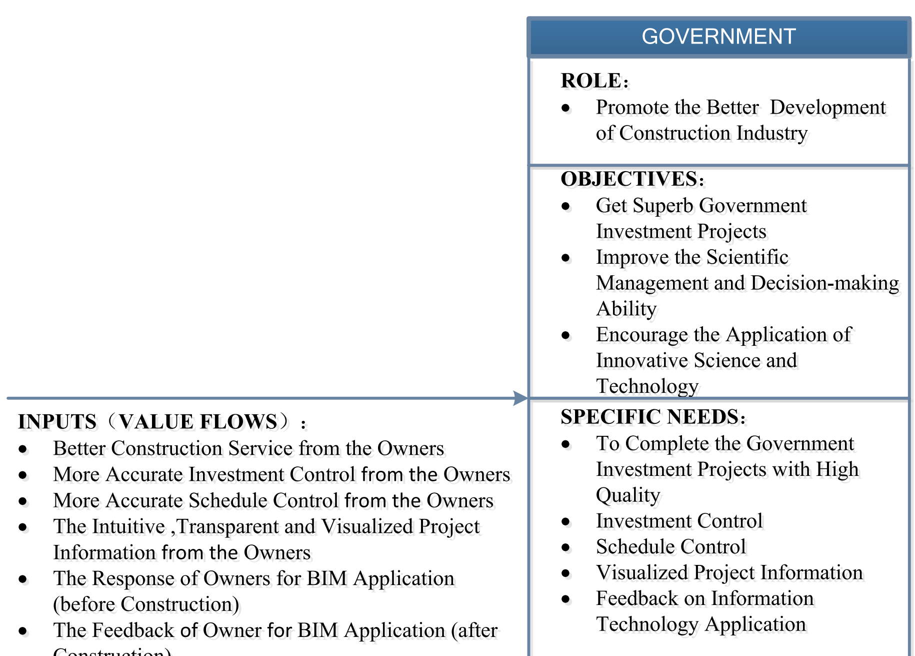

Fig. 2. Stakeholder characterization template (SCT) for an example of government.
Note: Interview questions for SCT development are available upon request.

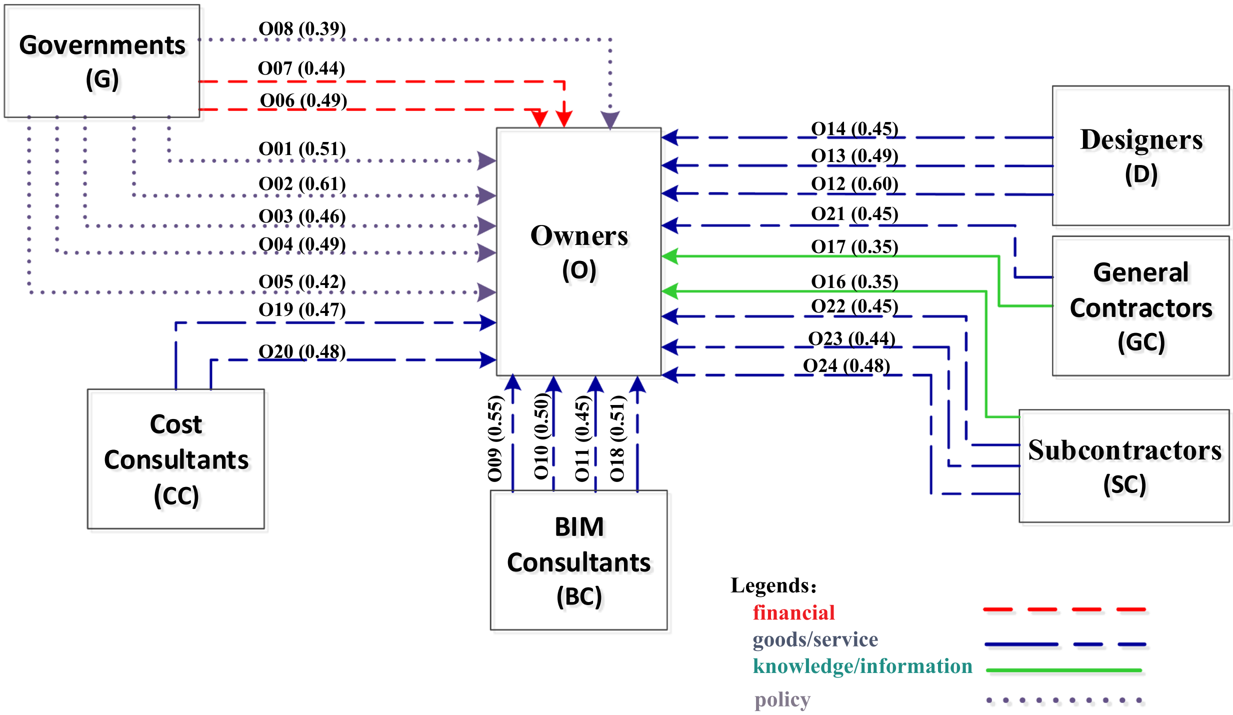

Fig. 3. Utility scores of all value flows pointing to owners. The unity score is in the bracket.

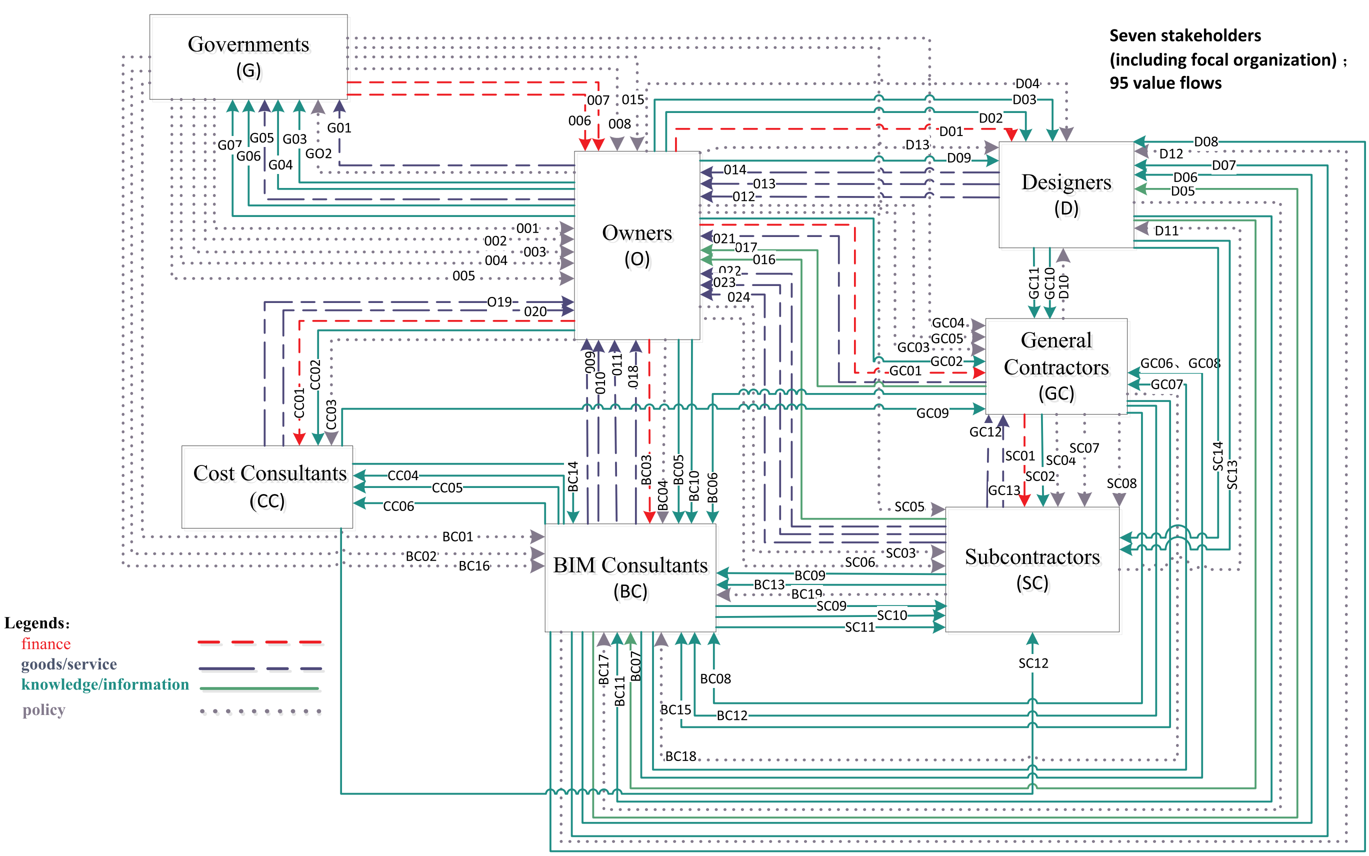

Fig. 4. The qualitative model of BIM-SVN that contains 7 stakeholders and 95 values flows.

ultimately established based on the scores of all the value flows, which are comparable and reflect the satisfaction level perceived by the recipient stakeholders and their level of desire for involvement in the relevant direct value exchanges. Taking the owners as an example, the results of the value flows are illustrated in Fig. 3.

4.3. Searching for value paths and calculating scores

Searching for value paths and measuring them is a complex process in a BIM-SVN network. Here, an organizational interdependent matrix tool was used to search for the overall value paths based on the algorithms of the adjacent matrix and the accessible matrix in graph theory. The pre-defined propagation rule in Eq. (1) calculates all the possible value paths for a focal organization. The score of each value path is inversely proportional to its length; the longer a path is, the more difficult it is for the focal organization to drive BIM because a longer path involves more considerations and there are greater uncertainties associated with the stakeholders. The multiplicative rule simultaneously reflects both the benefits and the costs of a value path describing the subjective utilities of each stakeholder, so a value path with a high score represents a critical drive that will promote the use of BIM. When analyzing a focal organization, the focus is on value cycles that are value paths beginning from and ending with that particular organization.

After searching the value cycles, network statistics can be calculated to analyze the BRC of stakeholders, important value flows, and the strategic implications of BIM use. Stakeholders choose to adopt BIM when they know they can realize their expected benefits. To seek out these stakeholders, the BRC of each stakeholder was measured using WSO (Eq. (2)); the relative importance of each value flow in BIM-SVN was also measured using WVFO (Eq. (3)). Focal organizations should pay attention to high scoring value flows as these flows play a critical role in promoting successful BIM implementations.

5. Results for the whole network

Following the four-step method described above, the whole network can be analyzed both qualitatively and quantitatively, as follows.

5.1. Qualitative model analysis

Once all the stakeholders and values flows have been determined, the qualitative BIM-SVN model can be established (see Fig. 4). Knowledge/information has the largest percentage (36 of the 95 value flows) of the four value flow categories in the BIM-SVN model, accounting for 38% of the total. This supports the argument that BIM is a repository of project information that facilitates interoperability and the exchange of information using related software applications [65]. The second largest percentage is that of policy flow (31% of the total), suggesting the significance of the policies emanating from various authorities, the support of owners, and mutual collaborations among stakeholders. Goods/services and financial flows account for 24% and 27%, respectively.

In Fig. 4, the majority of the value paths are composed of mixed value flow types. For example, this could be taking investment as an input and generating products or services as an output. This implies that driving BIM requires transforming one type of value flow into another for an individual organization. This is consistent with the experience of the experts interviewed for this study, who consider a BIM implementation to be a process that transforms the multi-type resources owned by stakeholders. The results obtained by the proposed BIM-SVN model therefore support the view expressed by Taylor [29], who argued that BIM is a process of collaboration among multiple organizations. Interestingly, of the 95 total value flows, 65 (69%) were intangible, which is more than double the number of tangible flows (31%). This highlights the importance of intangible values when adopting BIM.

Table 2
Numbers of value paths between any two stakeholders.

Stakeholders	G	O	BC	D	GC	SC	CC
G	**24,346**	3478	9036	23,174	16,000	26,623	27,507
O	7	**49,775**	1436	4087	2651	4794	3618
BC	5173	739	**49,215**	2663	2893	3713	1581
D	11,235	1605	3467	**40,394**	5590	7839	10,770
GC	8890	1270	1820	5748	**45,912**	3776	7434
SC	5054	722	1536	4324	4111	**45,706**	5397
CC	13,020	1860	5356	13,004	7363	10,334	**21,648**

Note: G = government; O = owners; BC = BIM consultants; D = designers; GC = general contractors; SC = subcontractors; CC = cost consultants.
The bold numbers on the diagonal represent special cases, namely value cycles that begin and end with the same stakeholder.
The underlined number represents that there are 49,775 value cycles for owners, the highest among all types of stakeholder.

5.2. Value path and cycle analysis

Searching out value paths with the organizational interdependent matrix tool reveals a number of value paths between any two stakeholders, as shown in Table 2. The bold numbers on the diagonal represent special cases, namely value cycles that begin and end with the same stakeholder. Since a value cycle includes all possible stakeholders involved with a focal organization, the diagonal number is maximal in a row. There are 49,775 value cycles for owners, the highest for any stakeholder. BIM consultants have the second highest number of 49,215 value cycles, followed by general contractors and subcontractors, with 45,912 and 45,706, respectively, while designers rank fifth with 40,394 value cycles. The lowest numbers relate to government and cost consultants, with 24,346 and 21,648, respectively, both of which are less than half the amount for owners.

The value cycles identified as important provide guidance for an organization seeking to formulate strategies to engage other stakeholders in using BIM. For each individual stakeholder, all value cycles were ranked based on their unity scores and identified a cycle that has a maximal score for any other stakeholder. The results are shown in Table 3. Taking G for instance, in the "O" column, "$\boxed{G}$→O02→$\boxed{O}$→G05→$\boxed{G}$ (0.41)" represents the maximal unity score (0.41) of a value cycle involving stakeholder "O."

In each row, the highest score is in bold and underlined, indicating that the corresponding stakeholder (in that column) would create maximal value in this value cycle. In the above case, where 0.41 is the largest in that particular row, G would have the most incentive to persuade owners ("O") to adopt BIM, scoring higher than any of the other stakeholders. In this example, both "G" and "O" would benefit the most (0.41) from this collaboration.

To summarize all the possible collaborative relationship scores, governments and owners would mutually generate the most value (0.41) from the collaboration and BIM consultants, designers, and cost consultants would benefit the most from collaborating with owners (achieving values of 0.32, 0.32, and 0.29, respectively). This result is explicitly aligned with the findings of previous studies, where owners have been found to be the most important organization in driving BIM implementations [13,23], while contractors and subcontractors create the most value from synergies and working together to utilize BIM. Both contractors and subcontractors should thus be encouraged to increase their level of BIM collaboration in order to fully realize their value. This is a new finding: previous studies did not identify this possibility because of their tight focus on the significance of the cooperation between designers and contractors to maximize value [28]. A possible reason for this discrepancy may be that more specialty subcontractors are involved and play significant roles in capital projects, which are typically highly complex. An integrated BIM platform across contractors and

Table 3
Maximal value cycle for individual stakeholder (in column), in 7 different focal organizations (in row) (unity score in brackets).

Value Cycles	Maximal value cycle containing a specific stakeholder						
	G	O	BC	D	GC	SC	CC
G → G	–	G → O02 → O → G05 → G **(0.41)**	G → BC01 → BC → O09 → O → G05 → G (0.20)	G → BC01 → BC → D06 → D → O12 → O → G05 → G (0.112)	G → GC04 → GC → O21 → O → G05 → G (0.091)	G → BC01 → BC→ SC10 → SC → O24 → O → G05 → G (0.106)	G → BC01 → BC → CC04 → CC → O19 → O → G05 → G (0.082)
O → O	**(0.41)**	–	O → BC16 → BC→ O09 → O (0.32)	O → D01 → D → O12 → O (0.32)	O → GC02 → GC →O21 → O (0.27)	O → SC03 → SC → O24 →O (0.18)	O → CC01 → CC → O19 → O (0.29)
BC → BC	(0.20)	**(0.32)**	–	BC → D06 → D → BC17 → BC (0.29)	BC → GC08 → GC→ BC18 → BC (0.26)	BC → SC10 → SC→ BC19 → BC (0.28)	BC → CC04 → CC→ BC14 → BC (0.15)
D → D	(0.112)	**(0.32)**	(0.29)	–	D → GC10 → GC → D10 → D (0.29)	D → SC13 → SC → D11 →D (0.28)	D → O12 → O → CC01 → CC→ GC09 → GC → D10 → D (0.088)
GC → GC	(0.091)	(0.27)	(0.26)	(0.29)	–	GC → SC02 → SC → C12 → GC **(0.33)**	GC → BC18 → BC →CC04 → CC → C09 → GC (0.151)
SC → SC	(0.106)	(0.18)	(0.28)	(0.28)	**(0.33)**	–	SC → O24 → O → CC01 → CC → SC12 → SC (0.123)
CC → CC	(0.082)	**(0.29)**	(0.15)	(0.088)	(0.151)	(0.123)	–

Note: Only the value cycles in the upper triangular matrix are shown as symmetric. G = government; O = owners; BC = BIM consultants; D = designers; GC = general contractors; SC = subcontractors; CC = cost consultants.
Bold and underlined numbers indicate the highest score In each row, which implies that the corresponding stakeholder (in that column) would create maximal value in this value cycle.

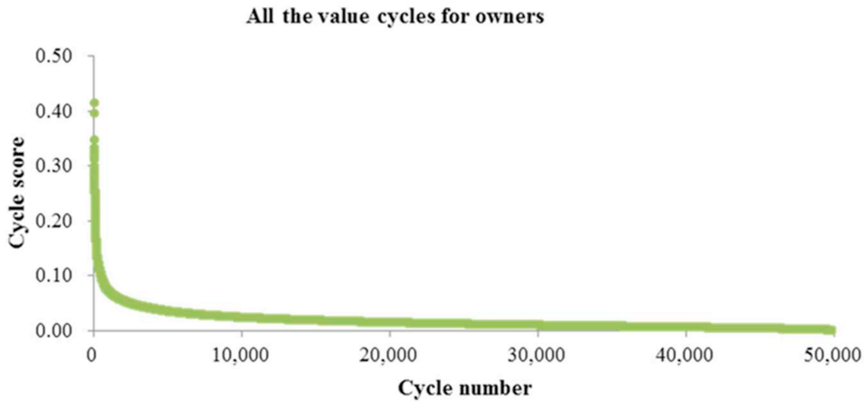

Fig. 5. The score distribution of all value cycles for owners.

subcontractors could contribute to improving both accuracy and productivity when fulfilling various kinds of specialized engineering requirements, for example.

6. Discussion: focal organization (owners)

As owners play a predominant role in BIM implementations [17], they are referred to as the focal organization in the following discussion. Based on the 95 value flows identified, 50 of which directly connect to owners, the proposed BIM-SVN model identified 49,775 value cycles involving owners. The distribution of their utility scores is shown in Fig. 5. The mean utility score of these value cycles is 0.018, and the maximum and minimum scores are 0.41 and 0.001, respectively.

As the score distribution in Fig. 5 shows, the utility score of the value cycles follows a power-law distribution. Setting the baseline to 0.01, 31,246 of the value cycles represent 62.77% of the total; only 461 have a score greater than 0.1, accounting for less than 1‰ of the total. This indicates that a small number of cycles possessing high scores can drive the value delivery in BIM implementations. These value cycles should therefore be subjected to in-depth investigation in order to develop strategies that maximize the effectiveness of BIM.

6.1. Critical value cycles

Ranking the value cycles based on their unity scores identified the top restricted exchanges (from cycle ① to ⑥) between the owners and each of the other six categories of stakeholders (see Fig. 6). An analysis of these exchanges could help owners understand their relationships to other stakeholders and thus propose appropriate strategies for using BIM.

In cycle ①, owners expect the highest value from government's “BIM-related policy support” (O02). Such legal support is the underlying premise of better BIM implementations [72] as it supports intellectual property agreements for data exchange, the classification of public and private data, and correspondence protocols [73]. The government is also expected to develop a suite of submission templates and guidelines to help professionals smoothly transfer from traditional 2D drawings to BIM in this cycle. Meanwhile, owners can gain the most value from BIM by providing “better design drawings” (G05) to the government. This is in line with the status quo in China, where BIM is primarily utilized to improve the quality of shop drawings through design coordination and design option analyses [74].

In cycle ②, the owners' provision of “cooperation and support” (BC16) can help improve the efficiency of BIM consultants, since the provision of BIM services is new to the market and the role of BIM consultants is not yet fully understood by construction stakeholders. BIM consultants are also expected to provide more “BIM-related training” (O09) to owners to ensure that they are familiar with BIM as a new way of working [8]. Improvements in training can also boost owners' BIM capacities and skills, which are essential to ensure the effective long-term use of BIM.

In both cycles ③ and ④, designers and cost consultants pay more attention to the “service fees” from owners (D01 and C01), and this is attributed to two causes. First, BIM is an additional service that goes beyond the traditional work scope, potentially increasing the workload and reducing organizational profitability. Consultants are thus naturally concerned about imposing additional BIM charges on top of the original service fees. Second, given that as yet there are no standardized service packages or universal pricing schemes for BIM, consultants must negotiate fees for individual projects. In cycle ⑤, owners are expected to provide explicit “BIM-related contract terms” (GC02) for general contractors, for example by incorporating various economic and contractual incentives [75]. This has been suggested previously; Love et al. [30] discovered that contract terms are significant when engaging stakeholders in using BIM. Compared to general contractors, subcontractors (in cycle ⑥) focus more on obtaining future opportunities (SC03) from owners.

The top three generalized exchanges can also be visualized as cycles ⑦ to ⑨ in Fig. 6. Generalized exchanges can thus serve as a basis for understanding the impacts of the indirect relationships among stakeholders, especially when it is difficult to engage them directly. These exchanges are particularly useful when developing “multi-party” strategies to promote BIM use. Taking cycle ⑦ as an example, governments begin to expect to obtain “better design drawings” (G05) from owners before moving on to satisfy the needs of BIM consultants by providing “BIM related laws, regulations, and standards” (BC01). BIM consultants then provide owners with “BIM-related training” (O09) to eventually deliver BIM value. By identifying these critical value cycles, owners can formulate efficient and effective ways to actively facilitate BIM implementation through understanding the specific value exchanges of key stakeholders.

6.2. Important stakeholders

From the perspective of the owners, the BRC of individual stakeholders can be measured by WSO; the results are shown in Fig. 7. As the owners appear in all the value cycles, their WSO score is 1.0. Based on the WSO results, BIM consultants are the second most-powerful beneficiary (0.91). They achieve prominence due to the emergence of widespread applications of BIM, becoming prioritized partners for the owners due to the high demand for their BIM expertise and skillsets, both of which are critical for adding value.

The second group is made up of the general contractors (0.78), subcontractors (0.77), and designers (0.70), all of whom are motivated to become engaged and create similar BIM-related value. As BIM builds

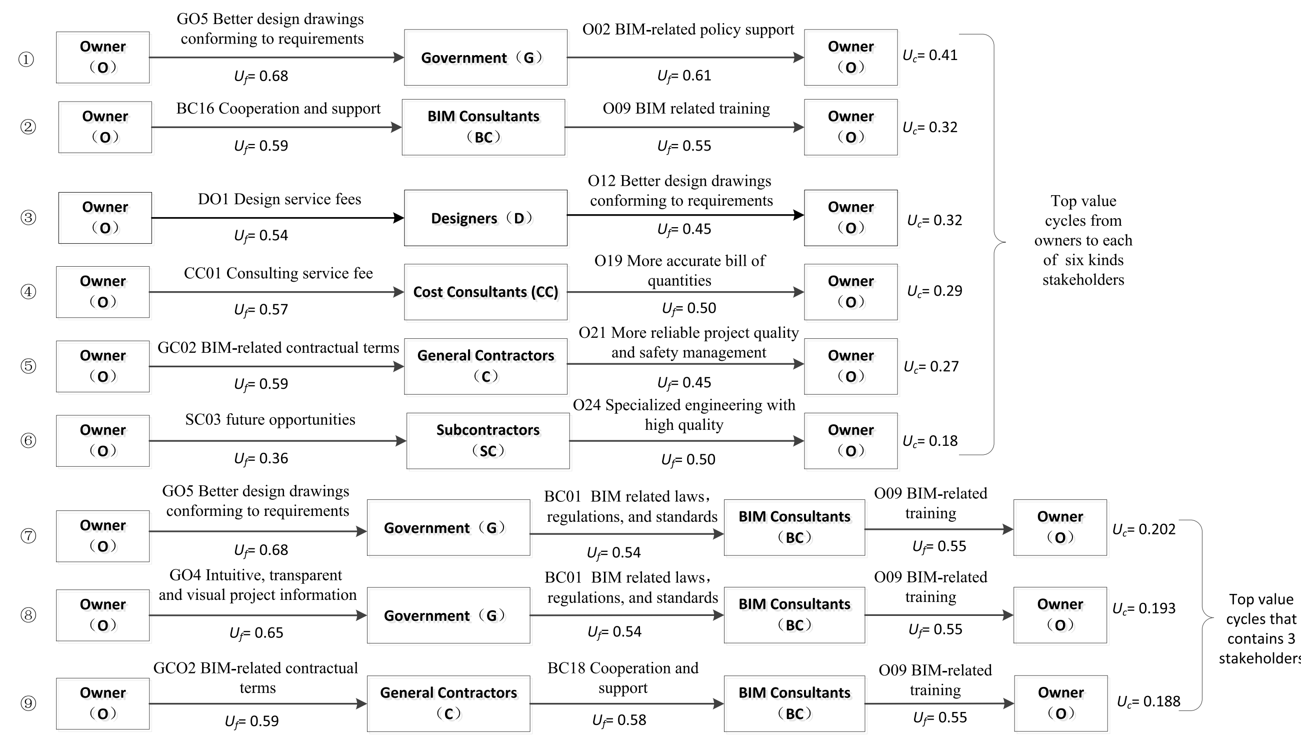

Fig. 6. Top Value Cycles for owners as a focus organization. Cycle ① to ⑥ represent the top value cycles from owners to each of six types of stakeholders, while cycle ⑦ to ⑨ represent top value cycles that contain 3 stakeholders.

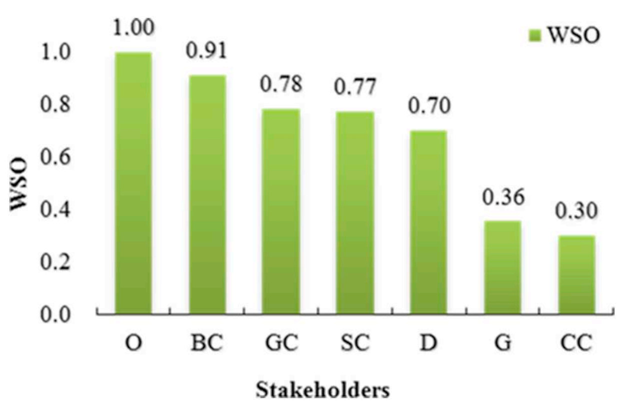

Fig. 7. The calculated result of Weighted Stakeholder Occurrence (WSO) for an individual stakeholder in BIM implementation.
Note: G = government; O = owners; BC = BIM consultants; D = designers; GC = general contractors; SC = subcontractors; CC = cost consultants.

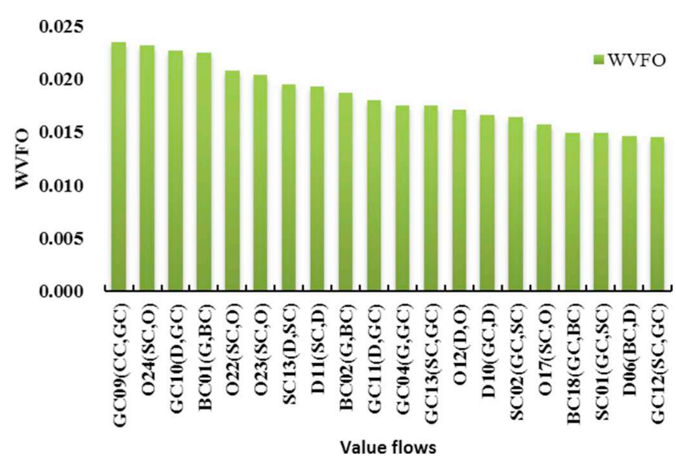

Fig. 8. Top 20 value flows for owners as a focus organization.
Note: value flows were coded with "recipient" and "number of value flows", with a bracket that shows the sender and the recipient of this value flow. For example, GC09 (CC,GC) is the ninth value flow received by general contractors (GC) and sent by cost consultants (CC). In the article, GC09 (CC,GC) is simplified as GC09.

in integrity, eliminates waste, increases feedback, and speeds delivery, it enables both contractors and designers to improve their organizational efficiency [8]. The slightly lower score for designers could be due to their somewhat ambivalent position on BIM, as BIM effectively replaces traditional 2D-based design practices [31].

Cost consultants have the lowest WSO score, which reflects actual practice: only a few cost consultants have initiated BIM implementations because of the complex and fragmented codes involved in cost estimates in China according to the experts interviewed for this study.

6.3. Important value flows

The WVFOs for all the value flows were calculated based on their attributes (the scores for their value flows) and structural positions in the BIM-SVN model. The results were then ranked and the top 20 value flows are shown in Fig. 8. Owners should pay particular attention to these highly ranked flows because they have a substantial impact on value delivery in a BIM implementation. The top three value flows are described in this section.

Among the 95 value flows, the "more accurate bill of quantities (BOQ) and cost estimate" (GC09) delivered from cost consultants to general contractors is deemed the most important. This may not be consistent with the findings of previous studies, which have suggested that detecting clashes in field installations is the most commonly required BIM function [25]. The finding may reflect the fact that low-price bidding is a pervasive strategy often used by general contractors seeking to become involved in capital projects, forcing general contractors to devote a great deal of attention to cost control by utilizing BIM. As a visual database of building components, BIM can provide accurate cost estimates automatically as well as helping to significantly reduce variability in cost estimates. The currently used cost estimation software is primarily employed to process monthly progress payments and final payments, but BIM allows users to dynamically integrate additional project data and information in parallel with the construction process. Cost consultants can thus utilize BIM-based software to conduct dynamic cost analyses, comparisons, and predictions, especially when engineering change orders occur, supporting better cost control by general contractors. Several BIM-based cost estimate software packages have been developed to perform these functions, including ToCoMan from TocoSoft, CI Estimator from CRC, and Estimator from Graphisoft [76]. However, this foreign software is not commonly applied in the Chinese construction market due to the different calculation rules for BOQ and the components involved in cost estimates. In China, companies such as Glodon BIM 5D and Epoint BIM 5D are currently developing BIM-based cost estimate software, making it likely that developing and utilizing 5D-BIM (3D plus schedule and cost) will become increasingly popular with cost consultants in China.

The second-most important value flow for owners is the provision by subcontractors of “specialized engineering with high quality” (O24). Specialized engineering plays a significant role in BIM-based projects, which are typically highly complex. BIM can add considerable value to projects such as the Shanghai Tower's doubly curved facade and the irregular steel structures used in recreation facilities such as Shanghai's new Disneyland. The subcontractors involved in fulfilling these specialized engineering requirements are normally nominated by the owners and have a high reputation in their respective fields. These specialty contractors can use BIM to plan every detail of their portions of the work and efficiently coordinate their activities with those of other contractors working on the same project [1]. For instance, subcontractors can use BIM to improve the accuracy of prefabricated components and increase the productivity of offsite prefabrication, thus reducing costs and time in the field, which is particularly beneficial for time-critical infrastructure projects [90]. The more streamlined process made possible by support from an integrated BIM platform across contractors and subcontractors could eventually contribute to both the project quality and schedule, which matters for the owners.

The third value flow, “Better design drawings” (GC10), has great importance because it is demanded by contractors. Collaborative BIM modeling is the most effective way to unambiguously convey the designers' intentions to the contractors using their drawings [77]. Precise drawings can also ensure unscrupulous bidders cannot take advantage of the discrepancies, errors, and omissions that are almost inevitable in 2D drawings. During the construction process, contractors can leverage accurate shop drawings in a visual way to align outcomes more closely with the owners' expectations.

6.4. Suggested strategies for stakeholders

Based on the top 20 value flows and the critical value cycles identified above, together with the critical stakeholders identified by WSO, a brief BIM-SVN consisting of fewer critical stakeholders and value flows can be constructed (Fig. 9). This serves as a visual tool for stakeholders to help them develop intuitive strategies to drive BIM use and thus fully realize the potential value of BIM. Based on this simplified model, five strategies are proposed in this section.

Firstly, innovative project delivery should be adopted to encourage proactive BIM collaborations among stakeholders and satisfy the diverse needs of the various construction practices. The traditional DBB approach limits the contractor's ability to contribute their knowledge to the project during the design phase (referred to D10 and D11) due to the fragmented and dispersed structure of the AEC industry. To address this issue, several versions of appropriate collaborative arrangements have been found to expedite BIM use, including integrated project delivery (IPD) and partnering [13,79]. Innovative project delivery is essential for stakeholders seeking to improve cooperation and achieve long-term gains though BIM. At present, the major applications of BIM are limited to conventional BIM capabilities such as visualization, design coordination, and clash detection, while more specialized functions such as structural analysis [80], building performance [81], environmental analysis [82], safety management [83], and offsite fabrication [84] (referred to GC13 and O24) are rarely used. The reason why certain BIM applications have been widely adopted and others have not is that the former generate visible and immediate benefits while the latter require collaborators to engage in practices that yield long-term value [88]. In a traditional contract with its short-term focus, stakeholders in the project network usually lack incentives to adopt BIM because they are unsure whether and when they will work together on another project. Greater attention to long-term gains can be encouraged by adopting new project delivery paradigms that are conducive to adjusting the existing socio-cognitive environment by introducing a stronger focus on “time and action” [89].

Secondly, owners should formalize the contractual regulation of BIM adoption and implementation by providing specific requirements to contractors (GC02). BIM implementations raise important contractual issues relating to responsibilities, risks, sharing, indemnities, data ownership, and associated copyright. Such issues must be articulated collaboratively upfront in formal contractual agreements [68], but these are yet to be addressed by the standard forms currently used in the AEC industry [9,13]. Once BIM terms have been institutionalized, all stakeholders will benefit from pre-defined BIM agreements collaboratively, including the general contractors and subcontractors (referred to SC01 and SC02).

Thirdly, owners should re-structure payment schemes by formalizing BIM service fees and changing the payment arrangements for BIM service providers (referred to D01 and CC01). Consultants have complained that BIM increases their workload and reduces their organizational profitability. Love et al. [33] advocated providing consultants with larger upfront payments to compensate them for the greater effort required early in the process as they develop a detailed BIM model. Alternatively, the BIM service fee could be determined in proportion to the BIM-related benefits gained by stakeholders [65,75] based on the WSO results, which indicate the BRC of individual stakeholders.

Fourthly, better BIM education and skill training for owners (referred to O09) is necessary to improve their professional quality and equip them to benefit fully from the possibilities that will open up due to the widespread use of BIM. These improvements in professional quality will enable them to 1) deliver precise project information (e.g., progress, cost, and quantity of resources) and high-quality drawings to the government agencies and owners commisioning the project, and 2) develop effective contract terms with other stakeholders (referred to G05, G04, G02). This strategy echoes the findings of existing studies, where researchers have suggested a need to rethink the curriculum used in educating building professionals, as the emergence of BIM is introducing a new paradigm that shifts the way design, construction, and maintenance of complex projects is carried out [78]. Arayici et al. [7] suggested that BIM implementations should engage owners, encouraging them to build up their skills and understanding, and minimize any potential resistance to change. To a great extent, education can ensure that all team members understand the potential of BIM and the importance of compliance when seeking to “drive the BIM train” [78].

Finally, governments should be committed to establishing an effective regulatory system for BIM implementations in the form of a comprehensive set of laws, policies, guidelines and open standards designed specifically to support Chinese BIM professionals (referred to BC01 and BC02) [11,72]. The government is responsible for diffusing innovative technologies via pilot and demonstration projects that develop best practices and operational guidance for various types of projects [72]. Similar policies have already been put into practice by the Shanghai government, contributing to the high adoption rate of BIM [85] in the city. Such policies are expected to be imitated by other cities

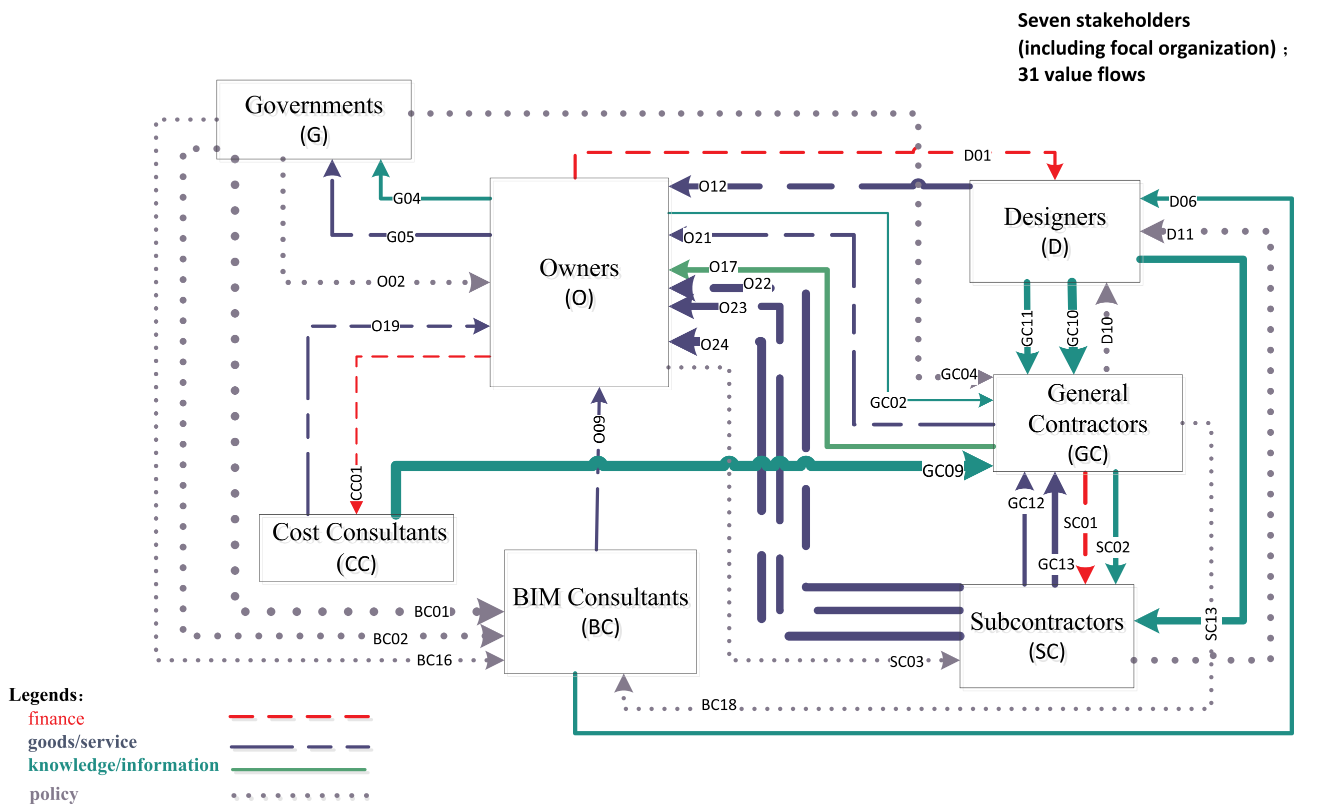

Fig. 9. A brief BIM-SVN consisting of key critical stakeholders and value flows. The size of each rectangle (referred to stakeholders) is proportional to its ranking of WSO, and the thickness of each flow is proportional to its ranking of WVFO.

in China in the near future.

7. Conclusion

BIM implementations are complex processes that involve multiple stakeholders, interdependent collaborations, and value exchanges, constructing a value network with heterogeneous value flows. To visualize and quantify the value network, this study presents a novel method based on SVN to help develop a better understanding of the value delivery mechanism and its impact on BIM stakeholders. By constructing a qualitative BIM-SVN model based on 7 key stakeholders and 4 types of value flows, all 95 of the value flows have been quantified and identified among stakeholders using the results of a questionnaire survey to assign a numeric score to each. In a focal organization analysis, a comprehensive search identified 49,775 value cycles, all of which started from and ended with the owners. The calculation of the stakeholders' BRCs and the occurrence of value flow revealed the vital roles played by critical value circles, key stakeholders, and important value flows. The discussion concluded by proposing five strategies to help owners support better BIM implementations.

The key findings of this study can be summarized as follows. From the perspective of the whole network, intangible value flows represented 69% of the total, more than double that conveyed by the tangible values (31%). In particular, "Knowledge/information" flows (38%), which are regarded as intangible value flows, were identified as the most significant among the four kinds of value flows in BIM implementations, followed by policy flows (31%), goods/services (24%), and financial flows (7%), echoing the limitations identified in previous studies, all of which ignored intangible values. From the perspective of owners' focal organizations, the three most beneficiary stakeholders that gain the most by promoting BIM use were identified as BIM consultants, general contractors, and subcontractors. Of the nine top-ranked value cycles, six were restricted exchanges and three general exchanges. Among the top twenty value flows, GC09 ("More accurate bill of quantity and cost estimate" from cost consultants to general contractors), O24 ("Specialized engineering with high quality" from subcontractors to owners), and GC10 ("Better design drawings conforming to requirements" from designers to general contractors) were found to be the most important for realizing BIM value delivery.

This study makes three key contributions to research in this area. First, the applicability of Social Exchange Theory (SET) and SVN was extended and validated in the context of the adoption of new technology (in this case, BIM) in the AEC industry. Compared to previous studies, which have rarely quantified multiple-type (both tangible and intangible flows) exchanges in SET and other network-based theories, our results highlighted the significance of intangible flows to promote value delivery among BIM stakeholders. Second, standardized values for the individual stakeholders in the BIM-use supply chain were created, allowing them to be characterized and compared and thus potentially contributing to benchmarking value creation, exchange, and realization for BIM services and wide-spread adoption. The third contribution is that a new way to visualize the value flows connecting relevant stakeholders has been proposed, helping both researchers and project stakeholders to explore key cycles in delivering BIM value and develop targeted strategies to improve project collaborations.

The findings of this study have several practical and policy implications. Firstly, the results reinforce the need to regard BIM implementations as complex and systematic activities, emphasize the need for firms in project networks to coordinate their efforts and develop interoperable business practices that enable them to capture the full value of BIM [29]. The new SVN model proposed here will help stakeholders understand the value trade-offs inherent in BIM application, allowing them to engage in effective multilateral negotiations and allocate resources more appropriately to meet their business objectives. Secondly, as the BIM-SVN method translates stakeholder needs into an input-output model, this will help focal organizations to trace "earned" or "weak" value exchanges in a network and adjust corporate decisions and business processes accordingly. Last but not least, the critical value cycles (or flows) identified in this study will help BIM policy-makers to formulate value-based instruments that promote stakeholder's "buy-in" and expedite the pace of large-scale BIM utilizations.

This study suffers from some limitations that require further study. First and foremost, the study considers only the main categories of stakeholders involved in the design and construction phases, without considering any detailed sub-classifications within each category. For example, subcontractors could be subdivided into facade sub-contractors, electromechanical sub-contractors, and so on, while BIM users during the operation and demolition phases will have quite different requirements. Further studies are recommended to extend the BIM-SVN model to make it more comprehensive by incorporating more stakeholder categories across the whole project lifecycle. Secondly, SVN analysis was designed to shed light on the value exchange and structural properties of multi-relation networks. The system model is thus static in nature, providing a "snapshot" of value distribution at a specific stage. Future research should explore the use of a dynamic analysis methodology to help researchers understand the reciprocal behaviors and responses of complex systems over time. Thirdly, the multiplicative rule adopted in this study represents a simplified way to quantify a value path by considering both benefits and costs. As more computational/analytical resources become available, individual value paths could be further segmented by applying different operation rules to reflect more subtle aspects such as "more value accumulated along a value path" and "more difficulties (costs) incurred to manage longer paths". Lastly, this study has focused on capital projects funded by government agencies in a Chinese context that were delivered by the Design-Bid-Build (DBB) method, so the application of these findings to other contexts should be undertaken with care. Appropriate adjustments, such as the consideration of different construction markets, project types, project delivery methods, locations and ownership (either public or private) should be considered. In the future, further exploration and sensitivity analyses should be conducted to achieve more detailed results.

Acknowledgments

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Appendix A. Scoring method for value flows

The utility score for each value flow (U_f) is calculated by the scores of its two attributes, i.e., "intensity of a need" and "importance of source in fulfilling a need". The score of "intensity of a need" is exponentially discounted with time, while the score of "importance of source in fulfilling a need" can be linearly differentiated, which ensures that value flows that are absolutely necessary will score significantly higher than other value flows that may be important, but not critical, see Eq. (A.1). However, the score of "importance of source in fulfilling a need" can be linearly differentiated, see Eq. (A.2). For each attribute, a five-point scale is adopted and the maximal sore is set as 0.98 rather than 1.0, because a value loop containing three links (each with a score of 1.0) would have the same score as a value loop with six links (each with a score of 1.0), which would be unreasonable since delivering value through a chain of six stakeholders would be much harder than delivering value through a chain of three stakeholders, and the scores should therefore reflect this. Furthermore, the scale begins with the lowest score of 0.11. Each successive response is a factor that is approximately 1.7 higher than the next-lowest response. A multiplicative utility function is then chosen to simplify computation, while ensuring positive correlations between utility and these two attribute scales, as in Eq. (A.3).

$$U_i(intensity) = 0.11 \times 1.7^{intesnsity} \tag{A.1}$$

$$U_s(source) = 0.11 \times source \tag{A.2}$$

$$U_f = U_i(intensit) \times U_s(source) = 0.0121 \times source \times 1.7^{intesnsity} \tag{A.3}$$

where *intensity* = 0, 1, 2, 3, 4, *source* = 1, 3, 5, 7, 9.

Take the value flow O01 "BIM-related laws, regulations, and standards" as an example to show the three calculation steps as follows.

Step 1: Respondent 1 assessed two attributions of value flow O01 – "intensity of a need,"

and "importance of source in fulfilling a need" in questionnaire of owners. Value flow O01 is regarded "extremely needed" (i.e., intensity = 4), and the source of the value flow (referred to government) is "extremely important" (i.e., source = 9). Thus, the score for these two attributes are calculated respectively based on Eqs. (A.1) and (A.2).

$$U_{i1} = 0.11 \times 1.7^4 = 0.92$$

$$U_{si} = 0.11 \times 9 = 0.99$$

Step 2: Calculated the total score of value flow O01 according to Eq. (A.3).

$$\mathrm{U_{f1} = U_{i1} \times U_{si}} = 0.92 \times 0.99 = 0.91$$

Step 3: Calculated the final score of value flow O01 by the mean score answered by 18 corresponding respondents of owners.

$$\mathrm{U_f} = \frac{\sum_{\mathrm{n}=1}^{18} \mathrm{U_{fn}}}{18} = 0.51$$

Thus, the score of value flow O01 is 0.51 as shown in Fig. 3.

Appendix B. Codes of stakeholders and value flows

Stakeholder	Code of Stakeholder	Number of needs (value flows)	Code of value flows
Government	G	7	From G01 to G07
Owners[a]	O	23	From O01 to O24, except O15[b]
BIM consultants	BC	19	From BC01 to BC19
Designers	D	13	From D01 to D13
General contractors	GC	13	From GC01 to GC13
Subcontractors	SC	14	From SC01 to SC14
Cost consultants	CC	6	From CC01 to CC06

[a] Including "quality supervision units".
[b] O15 was deleted after expert interview.

Appendix C. Codes, descriptions, categories and references for all value flows

Code[a]	Descriptions[c]	Category[b]	References
G01(O,G)	Better fulfilment of projects	GS	[1]
G02(O,G)	Response to BIM use	P	[72]
G03(O,G)	Feedback of BIM use	KI	[1,2,13,65]
G04(O,G)	Intuitive, transparent and visual project information	KI	[1,25,34,61,68,72,74]
G05(O,G)	Better design drawings conforming to requirements	KI	[1,2,61,74]
G06(O,G)	More accurate investment control	KI	[1,2,61,68,74]
G07(O,G)	More accurate schedule control	KI	[67]
O01(G,O)	BIM-related laws, regulations, and standards	P	[1,2,13,72]
O02(G,O)	BIM-related policy support	P	[1,2,13,72]
O03(G,O)	Guidelines for BIM use	P	[1,2,65,72]
O04(G,O)	BIM-based building approval submission system	P	[72]
O05(G,O)	Contractual template for BIM use	P	[1,2,13,64,65]
O06(G,O)	BIM-related budget	F	[13,64]
O07(G,O)	Return on investment for BIM use	F	[13,15,34,62,65]
O08(G,O)	Support for BIM use	P	[13,72]
O09(BC,O)	BIM-related training	KI	[2,13]
O10(BC,O)	Multi-dimensional BIM model	GS	[1,61,64,74]
O11(BC,O)	Schedule information based on 4D BIM	KI	[1,61,62]
O12(D,O)	Better design drawings	GS	[1,2,61,68,74]
O13(D,O)	More accurate design cost estimates	KI	[1,2,34,74]
O14(D,O)	Feasible solution for engineering change	GS	[74]
O16(GC,O)	Reduction in engineering change orders	KI	[1]
O17(SC,O)	Reduction in engineering change orders	KI	[1]
O18(BC,O)	Bill of quantities and cost estimate based on BIM	GS	[1,61,62,68,74]
O19(CC,O)	More accurate bill of quantity	GS	[1,25,61,62,68,74]
O20(CC,O)	More accurate cost estimate	GS	[1,2,25,61,62,68,74]
O21(GC,O)	Better project quality and safety management	GS	[1,34]
O22(SC,O)	Better project quality and safety management	GS	[1,34]
O23(SC,O)	High-quality design documents for specialized engineering	GS	[1]
O24(SC,O)	Specialized engineering with high quality	GS	[1]
BC01(G,BC)	BIM related laws, regulations and standards	P	[1,2]
BC02(G,BC)	Project approval system based on BIM	P	[1]
BC03(O,BC)	BIM service fee	F	[34]
BC04(O,BC)	The future opportunities	P	[30]
BC05(O,BC)	BIM-related contractual terms (modeling requirements, responsibilities, rewards, and risk-sharing)	KI	[1,61,64,65]
BC06(GC,BC)	Detailed documents (drawings, models, materials samples, etc.)	KI	[8]
BC07(D,BC)	Accurate and complete design documents	KI	[13]
BC08(GC,BC)	Detailed construction records	KI	[1]
BC09(SC,BC)	Detailed construction records	KI	[1]
BC10(O,BC)	Timely engineering change information	KI	[1,61]
BC11(D,BC)	Timely engineering change information	KI	[1,61]
BC12(GC,BC)	Clear and dynamically adjusted project schedule planning	KI	[67]
BC13(SC,BC)	Clear and dynamically adjusted project schedule planning	KI	[67]
BC14(CC,BC)	Complete bill of quantity	KI	[35]
BC15(GC,BC)	Complete unit price for items in bill of quantity	KI	[35]
BC16(O,BC)	Cooperation and support	P	[64]
BC17(D,BC)	Cooperation and support	P	[64]
BC18(GC,BC)	Cooperation and support	P	[64]
BC19(SC,BC)	Cooperation and support	P	[64]
D01(O,D)	Design service fees	F	[15]
D02(O,D)	BIM-related contractual terms (modeling requirements, responsibilities, rewards, and risk-sharing)	KI	[1,2,65]
D03(O,D)	Design requirements	KI	[13]
D04(O,D)	The future opportunities	P	[30]
D05(BC,D)	Consulting report for design optimization	KI	[1,13,34,61,62,74]
D06(BC,D)	Suggestions for design optimization	KI	[1,13,34,61,62,68,74]
D07(BC,D)	Accurate bill of quantity	KI	[1,2,68]
D08(BC,D)	Intuitive, transparent and visual project information	KI	[1,25,34,61,74]
D09(O,D)	Clear requirements for changes	KI	[1,61,68]

D10(GC,D)	Cooperation and support	P	[65]
D11(SC,D)	Cooperation and support	P	[65]
D12(BC,D)	Cooperation and support	P	[65]
D13(O,D)	Cooperation and support	F	[65]
GC01(O, GC)	Contract	KI	[15]
GC02(O, GC)	BIM-related contractual terms (modeling requirements, responsibilities, rewards, and risk-sharing)	P	[2,65]
GC03(O, GC)	Future opportunities	P	[30]
GC04(G, GC)	Effective supervision and inspection based on BIM	P	[72]
GC05(O, GC)	Effective supervision and inspection based on BIM	KI	[72]
GC06(BC,GC)	Constructability assessment report	KI	[1,2,13,61]
GC07(BC,GC)	Construction schedule simulation based on 4D BIM	KI	[1,2,25,61,62]
GC08(BC,GC)	Resource planning based on 4D BIM	KI	[25]
GC09(CC,GC)	More accurate bill of bill of quantity and cost estimate	KI	[1,2,34,61,62]
GC10(D,GC)	Better design drawings conforming to requirements	KI	[1,62]
GC11(D,GC)	Feasible solution for engineering change	GS	[74]
GC12(SC,GC)	High-quality design documents for specialized engineering	GS	[1]
GC13(SC,GC)	High-quality specialized engineering	F	[1]
SC01(GC,SC)	Subcontract	KI	[86]
SC02(GC,SC)	BIM-related contractual terms (modeling requirements, responsibilities, rewards, and risk-sharing)	P	[1,2,65]
SC03(O,SC)	Future opportunities	P	[30]
SC04(GC,SC)	Future opportunities	P	[30]
SC05(G,SC)	Effective supervision and inspection based on BIM	P	[72]
SC06(O,SC)	Effective supervision and inspection based on BIM	P	[72]
SC07(GC,SC)	Effective supervision and inspection based on BIM	P	[72]
SC08(GC,SC)	Coordination management	KI	[86]
SC09(BC,SC)	Constructability assessment report	KI	[1,61,74]
SC10(BC,SC)	Construction schedule simulation based on 4D BIM	KI	[1,61,62]
SC11(BC,SC)	Resource planning based on 4D BIM	KI	[25,74]
SC12(CC,SC)	More accurate bill of quantity and cost estimate	KI	[1,61,62,74]
SC13(D,SC)	Better design drawings conforming to requirements	KI	[1]
SC14(D,SC)	Feasible solution for engineering change	F	[74]
CC01(O,CC)	Consulting service fee	KI	[87]
CC02(O,CC)	BIM-related contractual terms (modeling requirements, responsibilities, rewards, and risk-sharing)	P	[1,2,65]
CC03(O, CC)	Future opportunities	KI	[30]
CC04(BC,CC)	Basic data for bill of quantity	KI	[1,2,61,68]
CC05(BC,CC)	Bill of quantity and cost estimate based on BIM	KI	[1,61,62,74]
CC06(BC,CC)	Cost analysis on engineering change	KI	[1,74]

[a] All value flows were coded with "recipient" and "number of value flows", with a bracket that shows both the sender and the recipient of this value flow, separated by comma. For example, G01(O,G) is the first value flow received by government (G) and sent by owners (O). In the article, G01(O,G) is simplified as G01.
[b] Finance = F, Goods/service = GS, Knowledge/information = KI, Policy = P.
[c] Original questionnaires to quantify value flows can be provided upon request.

Appendix D. Main acronyms and abbreviations in the SVN analysis

Abbreviations	Full name	Definition
SCT	Stakeholder characterization templates	A tool that can provide respective information that how stakeholders contribute their resources that they own to one another, and how they acquire desirable value from each other.
BRC	Benefit realization capability	Competences to organize and manage such that the potential benefits arising from the use of BIM that can be realized.
WSO	Weighted stakeholder occurrence	A measure of BRC and calculated by the occurrence of a stakeholder in corresponding value cycles, divided by all cycle scores for a focal organization.
WVFO	Weighted value flow occurrence	A measure of the relative importance of a value flow, calculated by the weighted occurrence of a value flow in all the value cycles for a focal organization.

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