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Reliability Evaluation Index for the Integrated Supply Chain Utilizing BIM and Lean Approaches

Abstract

Purpose – This research aims to develop an approach to assess the reliability of integrated construction supply chain via an integrated model of Building Information Modelling (BIM) and Lean Supply Chain (LSC). It reflects the synergistic workflow between BIM and LSC as a novel approach to improve reliability of the construction projects.

Design/methodology/approach –This research evaluated reliability of the BIM-LSC approach through a combination of entropy theory, Set Pair Analysis (SPA), and Markov Chain (EESM). An exploratory survey was conducted to collect data from 316 industry professionals experienced in BIM and LSC. Subsequently, multiple cycles of calculations were performed with indirect data inputs. Finally, a reliability evaluation index was established for the BIM-LSC approach and potential applications were identified.

Findings –The results show that the EESM model of BIM-LSC developed in this study can handle not only supply chain reliability evaluation at a given state, but also the prediction of reliability in supply chain state transitions due to changing project conditions. This is particularly relevant to the current environment of the construction project, which are characterized by an increasing level of complexity in terms of labor, technology, and resources interactions.

Research limitations/implications - Future research could consider the accuracy and validity of the proposed model in real-life scenarios with sparing efforts by considering both quantitative and qualitative data across the entire lifecycle of the projects.

Practical implications –This research offers a model to evaluate reliability of the BIM-LSC approach. The accuracy of BIM supply chain reliability analysis and prediction under an uncertain environment is improved.

Originality/value –The BIM-LSC reliability evaluation and prediction presented in this study provides a decent theoretical foundation to enhance understanding of the BIM-LSC in the construction project context.

Keywords: Building Information Modeling, Lean Supply Chain, Reliability Evaluation, Set Pair Analysis, Markov Chain.

Article Type: Research Paper.

1 Introduction

The rapid development and transformation of the global economy, with deepened business service specialization in parallel with pervasive and geographically-dispersed collaborations, have posed unprecedented challenges to supply chain managements (SCM) across industry sectors (Klimov and Merkuryev 2008). In the construction industry, supply chain integration can be especially difficult due to its high fragmentation (Shi et al. 2016). Furthermore, challenges are exacerbated by the uniqueness in the specificity of project delivery methods and an unwillingness of project participants to cooperatively share information due to the temporary nature of construction projects that can lead to difficulties in establishing trust and cooperation (Cheng et al. 2010).

Recently, emerging approaches including Building Information Modeling (BIM), Lean Construction and Green Building methods are reshaping the global business environment of the construction industry (Zuo et al. 2017, Zuo and Zhao 2014, Ding et al. 2015). Best practices in adoption and implementation of these applications have shed light on the strategies to reduce waste, improve productivity, promote performance and maximize added value and profitability through a project’s life cycle (Ahuja, Sawhney and Arif 2017). The integrated BIM-Lean Supply Chain (BIM-LSC) concept is gradually gaining recognition by the industry (Dave et al. 2013, Sacks et al. 2010). As a synergistic convergence of technological advancement and business process improvement, BIM-LSC has been applied to holistically and strategically address socioeconomic and environmental sustainability goals (usually defined as the triple-bottom-line) and help accomplish green project outcomes (Fernández-Solís and Mutis 2010, Ahuja et al. 2017, Wu and Issa 2015, Ahuja et al. 2014).

To elaborate on BIM-LSC interaction, BIM serves as the technological and communication platform for related project life-cycle information to be generated, exchanged, managed and shared among project stakeholders with stipulated roles and responsibilities, under specific contractual protocols (Hjelseth et al. 2010). By eliminating information silos and avoiding communication gaps, BIM offers a reliable, flexible and functional foundation to more streamlined business processes and efficient project execution, which can eventually lead to waste reduction, time and budget savings, improved profitability and client satisfaction (Azhar 2011, Bryde, Broquetas and Volm 2013). Nevertheless, to fully exploit the benefits of BIM, human behaviors play an essential role rather than technology (Smith and Tardif 2009, Fernández-Solís and Mutis 2010). In addition, originated from the automobile and manufacturing industry, lean principles can provide project teams with the desired mechanism to deploy, manage, monitor successful BIM project platform execution, and drive more efficient utilization of resources and energy to achieve sustainability performance and goals (Sacks et al. 2010, Ahuja et al. 2017, Khodeir and Othman 2016, Ahuja et al. 2014). In this paper, BIM-LSC refers to the synergistic use of BIM technology and Lean principles in the construction supply chain in order to enhance information-driven collaboration capabilities of project teams so that business process performance can be improved in delivering capital projects.

BIM-SLC has gained wide attention. These include general discussion and documentation of the BIM-Lean interaction evidence (e.g. Sacks et al. 2010), detailed analysis and delineation of the interactive matrix and dynamics (e.g. Bin, Bo-sheng and You-qun 2011), and identification of enablers, methods, tools and strategies to facilitate its integration and measuring its maturity (e.g. Dave et al. 2013). Nevertheless, despite the plethora of available tools, the evaluation of *reliability* as a major success factor in SCM has not been investigated in the context of BIM-LSC. Time, budget and quality are typical constraints in project management (Ford and Bhargav 2006). **Therefore, this paper defines BIM-LSC reliability as "the ability to deliver a capital project with a specified time, budget and quality conditions, under the influence of a variety of uncertainty factors, to deliver green outcomes using the lean production process and BIM technology"**. In line with the temporal nature of construction projects, project-based BIM-LSC faces challenges of instability, fragmentation, and the disjointedness between project design and construction as inherent characteristics of construction projects. At the same time, BIM-LSC focuses on multi-stage production and multi-stakeholder. The nature of this phenomenon emphasizes the need for high reliability in supply chain interaction to reduce uncertainty. As the supply chain hierarchy in contemporary construction projects becomes increasingly complex, uncertainty factors can severely and adversely affect the normal operation of the supply chain, which necessitates better understanding, evaluation, and prediction of its reliability (Mahnam et al. 2009).

Research on BIM and Lean adoption and implementation in the construction supply chain has been proliferating. Existing studies have largely dealt with lean construction and BIM separately. There is no accurate approach to assess the reliability of integrated construction supply chain via an integrated model of BIM and LSC. The core operation and success of lean construction depend on the process efficiency of information integration. Therefore, the implementation of lean construction without an appropriate platform like BIM can lead to the loss of technical advantages on the effective sharing of information. This study focuses on the synergy of both BIM and Lean, without reliance on qualitative interaction measurement (e.g. qualitative methods), which can provide greater precision in the evaluation and prediction of reliability measures to guide future BIM-LSC management. This research aims to fill in this gap by applying the appropriate theory of BIM-LSC and propose an integrated evaluation approach to achieve the accurate analysis of BIM-LSC Reliability.

2 Literature Review

The literature review focuses on the reliability evaluation of BIM-LSC. The basic connotation of BIM-LSC was firstly studied, the evaluation indicator was discussed, and the previous reliability evaluation models were reviewed. The scope is shown in Figure 1.

<< Insert Figure 1 >>

Fig. 1. Scope of Literature Review

2.1 BIM and Lean Supply Chain

Among a wide range of supply chain studies, Pryke (2009) defined the supply chain as the focus of more effective ways of creating value for clients and as a vehicle for innovation and continuous improvement. Current research on the construction industry's SCM can be roughly divided into two categories: 1) project-centered SCM research and 2) enterprise-centered SCM research. This study focuses on the first category. The application of supply chain into BIM and lean projects supports the information interoperability of BIM and lean workflow (Dave 2013).

Previous studies on BIM-LSC have focused on new business processes that are driven by rapid BIM adoption and implementation, and the desired transition of contractual relationship and partnership among project stakeholders. Due to the dynamic interaction and synergistic convergence of BIM and Lean (Sacks et al. 2010), BIM-LSC features the unprecedented use of information technology and critical needs for the project information management (Dave et al. 2013). Thus, BIM-LSC is data-intensive and information-centric (Tommelein, Ballard and Kaminsky 2008). The integration of these concepts has been studied extensively. For example, the process of prefabrication housing production from manufacturing and logistics to the on-site assembly by integrating the BIM platform with lean construction has been simulated. Furthermore, Irizarry et al. (2013) combined BIM technology with geographic information system (GIS) to construct a visualization model of the material supply chain to perform model-based material takeoff. Using the reinforced concrete supply chain as a case study, Aram et al. (2012, 2013) demonstrated that BIM technology could significantly improve construction supply chain efficiency via automation and fluency of its information exchange. Yu, Lv and

Zhang (2016) proposed a roadmap of applying BIM technology for improved construction SCM and established a BIM-based SCM information system framework. Wen, Wang and XIa (2009) proposed to build a lean construction supply chain model with modular thinking to improve the transparency of information in the supply chain. Further, Dave et al. (2013) acknowledged that high synergistic effect between BIM technology and Lean, and proposed a systematic strategy to adopt BIM-LSC to ensure that information is effectively synergized throughout the project lifecycle.

Previous studies indicate that BIM-LSC plays an important role in the construction industry. The characteristics and key attributes of each project phase are scrutinized in terms of early design, design and detail, construction, fit-out and handover, and facilities maintenance (Koseoglu et al. 2018, Machado et al. 2016).

<< Insert Figure 2 >>

Fig. 2. BIM and Lean Workflow

Note: This workflow is in line with Table 1.

2.2 Project-based BIM-LSC Reliability Evaluation Index System

Supply chain reliability provides a theoretical background to quantify supply chain risks and uncertainties (Ha et al. 2018). Thomas (2002) first introduced the engineering reliability theory in SCM and defined the supply chain reliability as “the ability to complete a given task at a specified time and other conditions”. Liu and Luo (2007) considered the supply chain operations reference model and defined supply chain reliability from the enterprise perspective as the ability of the supply chain to achieve normal operations for a period. Mu (2010) approached the problem from a complexity theory position and defined reliability as the likelihood of meeting customer needs at the time, quantity, and quality required by the end customer. Similar studies on the scope of reliability and reliability evaluation include Zhao and Yang (2007) and Zhang (2012). Therefore, this paper defined the reliability in BIM and lean background as “the ability to deliver a capital project with a specified time, budget and quality conditions, under the influence of a variety of uncertainty factors, to deliver green outcomes using the lean production process and BIM technology”.

Currently, there are limited studies that have assessed the reliability of BIM and Lean integrated supply chains, so the relevant reliability evaluation index system needs to be developed. The UK Construction industry research and information association (CIRIA) links organizations with common interests and facilitates a range of collaborative activities that help improve the industry. CIRIA published the CIRIA C725 Lean and BIM Guidebook (Dave et al. 2013): *Implementing lean in construction: lean construction and BIM*. This guide was submitted to the British government and represented accurate and authoritative information on the joint application of Lean and BIM. It was the first of its kind and compiled both academic and professional knowledge incorporated in its development, and it articulated the main tools and techniques that are applied in Lean and BIM projects.

To establish a comprehensive and responsive index system to evaluate the reliability of BIM-LSC situation, Lean and BIM workflow is divided into five stages (See Fig.2) throughout the entire life cycle of the project according to the CIRIA C725 Lean and BIM Guide. It consists of the primary indicators that are subdivided into the secondary indicators (see Table 1).

Table 1. Proposed BIM-LSC Reliability Evaluation Index System

<< Insert Table 1 >>

2.3 Supply Chain Reliability Evaluation and Prediction model

Supply chain reliability has attracted substantial research attention in the broader supply chain management domain. In the investigation of reliability evaluation and prediction methods, Qian et al. (2015) used the basic theory of Markov process to dynamically analyze the reliability of supply chain in manufacturing enterprises and highlight the change of supply chain failure rate and reliability. Yuxiong and Gengfeng (2017) carried out the reliability evaluation of distributed integrated energy system based on a Markov chain Monte Carlo simulation. In the case of certainty and randomness of logistics supply capacity, Wu and Lu (2014) used the differential method and Markov theory respectively to establish the logistics enterprise reliability measurement model, where the discrete time Markov chain was used to represent the time schedule of task completion under random conditions. Deng et al. (2016) established the triangular fuzzy analytic hierarchy process to evaluate supply chain reliability based on triangular fuzzy numbers, this model overcomes the shortcomings of traditional weight calculation. Further, Wu et al. (2015) used the SPA theory and the fuzzy logic theory to evaluate the reliability of a solid rocket motor design scheme and provided a new solution for the uncertainty and fuzziness in the reliability assessment. Lin and Mu (2006) discussed the stability of order-based supply chain systems based on SPA from the perspective of the relationship between the various aspects of the supply chain and provided theoretical guidance on supply chain management. In the field of aviation maintenance safety assessment, Zhang et al. (2016) combined SPA theory with Markov chain and described the safety level of aviation maintenance and predict its safety dynamics trends.

However, the method to calculate the reliability in an uncertain environment is limited. This limitation hinders the promotion of BIM and lean approach in the construction industry.

2.4 Knowledge Gap

The synergies of BIM and Lean has gained an increasingly level of recognition. However, there are very limited studies on BIM-LSC reliability evaluation and prediction. These existing studies predominantly focused on the static assessment of reliability status at a certain period of time to identify safety levels, with less focuses on future reliability states and its dynamic trends (Peng et al. 2017, Zhang et al. 2016). Little attention has been paid to the measurement roles of information (entropy) in the reliability evaluation (Short and Wehner 2010). Information is a key measurement indicator for the degree of systematic ordering, and entropy is a measurement of the degree of system disorder. BIM-LSC, as a highly integrated information chain, can significantly benefit from the use the entropy method to measure the amount of BIM information provided by the BIM-LSC indicators. This assists in targeting the evaluation of BIM-LSC reliability and provides the precise prediction. Meanwhile, current methods experience difficulties in the quantitative analysis and prediction of the stability of BIM supply chain under uncertain environment. In order to predict the reliability of the supply chain, it is necessary to consider the orderly state transfer between nodes in the supply chain.

This research attempts to address this gap. Motivated by this imperative need to measure and respond to BIM-LSC reliability, this research reviewed and identified key reliability indicators for BIM-LSC, and adopted an integrated approach to develop a BIM-LSC reliability evaluation model. The proposed model relied on the entropy method to determine the weighting factor of the reliability indicators, and SPA to describe the degrees of connection between indicators in BIM-LSC. Finally, the Markov chain process was employed to predict reliability transitions when the status of individual indicators and their dynamics had changed. To demonstrate the potential application of the proposed model, a multi-cycle calculation was performed with indirect data inputs through an exploratory survey.

3 Methodology

The integrated approach proposed by Zhang and Wu (2007) and Zhang et al. (2016) was employed in this study to develop the reliability evaluation and prediction model. In this framework, the innovative quantitative analysis methods combining entropy weight method, SPA, and Markov chain prediction were used to evaluate and predict the reliability of BIM supply chain under uncertain environment. Firstly, the entropy weight method and SPA method were used to explore the key factors and influence mechanism of the reliability of BIM-LSC and assess the reliability of BIM supply chain under uncertain environment. The premises of SPA method is to grasp the weight of the influencing factors. Due to the complexity of the supply chain system, the method with higher subjectivity (e.g. AHP) has a significant deviation from the weight of the influencing factors. Therefore, using the entropy method with extremely high adaptability and objectivity to obtain the index weight has certain advantages over the method using AHP. Then, the Markov chain prediction method was used to propose the short-term prediction method of BIM supply chain reliability uncertain environment based on the impact analysis. Finally, a possible application of the proposed model was demonstrated through multiple cycles of calculation with indirect data inputs through an expert survey conducted among industry professionals that have BIM and Lean project experience, due to the lack of sufficient empirical BIM-LSC data.

The following steps were implemented to establish the Expert survey, Entropy method, SPA theory, and Markov chain (EESM) model comprising in Figure 3.

<< Insert Figure 3 >>

Fig. 3. EESM model

3.1 Expert Survey to Scale the Project-Based BIM-LSC Reliability Evaluation Index

To test the model, the first step was to apply the entropy method for reliability indicators' weight coefficients calculation. The initial values of the five sets and a total of 17 BIM-LSC Reliability evaluation indicators were assigned. As stated, there is currently a lack of first-hand BIM-Lean project information. This research used an alternative approach by collecting subject matter experts' perception values of these indicators using a survey questionnaire to capture the *"BIM-LSC Reliability Impact Factor"*, and conducted a comprehensive online and offline (paper-based) survey with a convenient sample to industry professional, project managers or consultants who have at least three years of experience in BIM-based projects. For each of these 17 indicators, the participants were requested to rate each factor's impact on BIM-LSC reliability on a 5-point Likert-type scale, where "1" was for No impact, "2" for Minor impact, "3" for Neutral, "4" for Moderate impact and "5" for Major impact. A total of 600 online/offline questionnaires were distributed and 338 completed questionnaires were collected, with a response rate at 56.3%. Prior to data analysis, data screening was implemented to inspect data for errors that involves checking raw data and identifying outliers. Eventually, a total of 316 valid datasets were obtained (see Appendix I). The mean values of the Likert scale impact factor ratings were then assigned to the 17 indicators as their initial values for the weight coefficient calculation with the entropy method.

3.2 Entropy Method to Calculate the Index Weight of Project-Based BIM-LSC

Entropy method is an objective weighting method. In this research, it was used to calculate the information entropy of the indicators based upon the influence of the degree of relative change of indicators on the overall index system. The value of the information entropy of each indicator was then directly associated with the indicator's weight coefficient (Lu and Kang 2009). The entropy method revealed the degree of orderliness and effects of information delivered via the indicator. Therefore, it has a certain degree of objectivity to determine the weight coefficient of each indicator using the evaluation matrix that is composed of normalized values of all indicators in the index system.

While for BIM-LSC, BIM is a process/platform for creating and managing the project information– before, during and after lean construction principals have been applied. BIM-LSC face challenges in the disorder of system information in information integration management to evaluate the reliability. Entropy is the appropriate method to quantitatively measure the disorder of system information. To a degree, entropy offers a useful proxy to measure the information between BIM and Lean construction, which integrates through the core connection of information extraction and measurement.

3.3 SPA to Determine the Degrees of Connection as Expression of the Reliability Levels

SPA theory could deal with various uncertain information such as inaccuracy, inconsistency and incompleteness, discover the hidden information and reveal potential laws (Jiang et al.

2003). Therefore, it is sensible that this paper adopted SPA to analyze the reliability of the supply chain under the uncertain environment. Meanwhile, this paper simulated the supply chain with Markov chain and simulated the supply chain service process with Markov chain node state transition, which fully reflected the dynamics of the supply chain and made the prediction closer to reality. The combination of the two methods solved the dilemma of quantitative analysis of previous research methods and improved the accuracy of BIM supply chain reliability analysis and prediction under uncertain environment.

The basic concepts of the SPA are the *set-pair* and *connection degree*. The so-called set-pair represents a pair that consists of two mutually related sets. Based on the analysis of specific characteristics, the relationship between the two sets can be classified and described in a quantitative way and has the following expression of connection degree.

Given two sets v and u , the set pair is expressed as $H = (v, u)$. Equation (1) calculates the connection degree of the two sets:

$$\mu = \frac{S}{N} + \frac{F}{N} i + \frac{P}{N} j = a + bi + cj, where \quad a + b + c = 1 \tag{1}$$

3.4 Markov Chain Model to Build States Transition Probability Matrix

The supply chain is an extremely complex system with fuzzy and rough information, which has significant uncertainties (Ebrahimy et al. 2011). Meanwhile, the supply chain is composed of many enterprise nodes. The operation of the supply chain requires enterprise nodes to update their status constantly and orderly so that the supply chain has obvious dynamics (Towill 2003, Towill 1982). The status of the supply service is either reliable or unreliable, while it may shift during a certain period. Moreover, the status of the service provided in each period is only related to the status of each operation link of the supply service in that time and is independent on the supply service before the period. The randomness and aftereffect less match the requirement of the Markov chain. Therefore, this paper adopted Markov chain to simulate the supply chain and realizes the dynamic prediction of the reliability of the supply chain. It is more dynamic and more realistic than the general static methods used in the previous studies.

System reliability depends on the reliability of the subsystems that make up the system and the organization of the system itself. The characteristics of reliability in this paper are as follows:

Reliability = The probability that the system will complete the supply task on time
= 1 - The probability that the system will not complete the supply task on time
= 1 - (Failure Rate - Maintenance rate × Failure Rate)

Each supply operation link is independent of each other from the perspective of reliability, that is, the problems in each operation link of the supply service are mainly caused by the operation failure of the link itself, and are not affected by other operation links, nor affect other operation links. However, any problem in one of the operations will affect the overall supply service. Therefore, it is possible to study the state transition of each operation link of the supply service from the supply operation flow, so as to predict the reliability of the supply service and its operation links.

Given E is the probability space, and $\{C\ (n), n \geq 0\}$ is an integer random sequence defined in the probabilistic space. If $m \geq 1$, C ($t1$), C ($t2$), ... , C (tm) corresponding to C (n) for $t1$, $t2$, ..., tm (where $t1 < t2 < \ldots < tm$) (tm) meet the conditions:

$$\mathrm{P}\big(\mathrm{C}(\mathrm{tm})\big)\big|\mathrm{C}(\mathrm{tm}-1), \mathrm{C}(\mathrm{tm}-2), \ldots, \mathrm{C}(\mathrm{t1})\big) = \mathrm{P}\big(\mathrm{C}(\mathrm{tm})\big)|\mathrm{C}(\mathrm{tm}-1) \tag{2}$$

Where $\{C\ (n), n \geq 0\}$ is named Markov Chain.

The Markov chain shows that the observed value of {C (n), $n \geq 0$} at tm time is only related to the value of time *tm*-1, regardless of the observed value at earlier time, and P (*C* (*tm*) | *C* (*tm*-1)) is the conditional probability, also known as state transition probability.

3.5 A New Approach for BIM-Lean Supply Chain Reliability

The following provided details of the new quantitative integrated approach for reliability evaluation and prediction of project-based BIM-LSC.

3.5.1 Weight Calculation of Evaluation Indicators Based on the Entropy Method

According to Su and Yang (2009) and Benedetto et al. (2015), the following four steps were carried out to determine the indicators' weights in the BIM-LSC reliability index system.

Suppose there are *m* units and *n* indicators to be evaluated, through the formation of the evaluation matrix and the standardization of the evaluation matrix, the entropy of the system can be defined as H_t, and the weight coefficients W of indicators could be calculated as Formula (3)

$$\mathrm{W} = (\omega_t)_{1\times n} \ , \omega_t = (1 - H_t)/(n - \textstyle\sum_{t=1}^{n} H_t) with \textstyle\sum_{t=1}^{n} \omega_t = 1 \qquad (3)$$

3.5.2 SPA-based Reliability Evaluation Model

Based on the practical characteristics of the BIM-LSC Reliability, this research assigned each indicator with three possible reliability levels, including *reliable* (*S*), *quasi-reliable* (*G*) and *unreliable* (*U*), in the order of descending reliability. Specifically, when applied to reliability evaluation, *reliable* (*S*) means acceptable reliability, while *quasi-reliable* (*G*) means acceptable reliability with precaution and *unreliable* (*U*) means unacceptable reliability with a need for rectification measures. *S*, *G*, and *U* should also satisfy the Equation (4):

$$\mathrm{S} + \mathrm{G} + \mathrm{U} = 1 \tag{4}$$

Where N is the total number of characteristics of a set pair; S is the number of identity characteristics; P is the number of contrary characteristics of two sets; $F = N - S - P$, is the number of the characteristics of these two sets that are neither identity nor contrary. The ratio $\frac{S}{N}$ (or a) is the identity degree of two sets; $\frac{F}{N}$ (i or b) is the discrepancy degree of two sets, and $\frac{P}{N}$ (or c) is the contrary degree of two sets. Meanwhile, j is the coefficient of the contrary degree and is specified as 1. As the coefficient of the discrepancy degree, i is an uncertain value between -1 and 1, i.e. $i \in [-1, 1]$, in terms of various circumstances. The uncertainty of the discrepancy degree of two sets is eliminated when i is specified as -1 or 1 and will increase when i is approaching zero.

In the process of reliability evaluation of the BIM-LSC, this research defined the indicator's actual states as E, while the ideal states as U. Then, sets E and U will form the pairs $H = \{E, U\}$, which was then used with SPA method to determine the *identity degree*, *discrepancy degree* and *contrary degree*.

To determine the overall reliability of BIM-LSC, the compound connection degrees of the collection of indicators was calculated as shown in the equation below:

$$\begin{aligned}\mu &= a + bi + cj \\ &= \sum_{k \in S} \omega_k + \sum_{k \in G} \omega_k \cdot i + \sum_{k \in U} \omega_k \cdot j\end{aligned} \tag{5}$$

Where,

$$a = \sum_{k \in S} \omega_k,\ b = \sum_{k \in G} \omega_k \cdot i,\ c = \sum_{k \in U} \omega_k \cdot j \tag{6}$$

It should be noted that ω_k refers to the weight of reliability index, which is generated by Equation (10). Let $i = 0$, $j = -1$, then the reliability Connection Degree $\mu \in [-1, 1]$. According to the average principle, the values of μ represent corresponding reliability levels. In other words, $-1 \leq \mu \leq -0.333$ designates as *unreliable* or *U*, while $-0.333 < \mu < 0.333$ designates as quasi-*reliable* or *G*, and $0.333 \leq \mu \leq 1$ designates as *reliable* or *S*.

To further explain the system dynamics of BIM-LSC and elaborate on the possible reliability level variation of each indicator within the established reliability index system, Table 2 summarized the possible set pair potentials conditioned on comparisons of the sizes of indicators with the specific reliability levels, i.e. *S*, *G* or *U*, as suggested by Zhang (2012) and Zhang et al. (2016). The primary comparison was made between the sizes of *S* indicators and *U* indicators. Specifically, if the size of *S* indicators > size of *U* indicators, the set pair potential is considered to be "*Direct*"; otherwise, if the size of *S* indicators = size of *U* indicators, the set pair potential is "*Balanced*"; and finally, if the size of *S* indicators < size of *U* indicators, the set pair potential is "*Inverse*". Under each of the three primary set pair potential groups, two additional secondary comparisons were made between the sizes of *S* and *G* indicators, and the sizes of *U* and *G* indicators, respectively, which yielded further granularity of set pair potentials, as shown in Table 3. As a result, a total of 13 different set pair situation scenarios were recorded, which corresponded with a particular outcome of the BIM-LSC reliability. Based on these evaluation results, the project team can take the corresponding preventive measures to reduce and avoid the risk of potential BIM-LSC failures.

Table 2. Set Pair Situation and Corresponding BIM-LSC Reliability

<< Insert Table 2 >>

3.5.3 Markov Chain-based Reliability Prediction Model

From a system dynamics point of view, the Markov Chain explains the reliability changes of a system (i.e. BIM-LSC in this case) which are caused by the reliability changes of individual indicators in the system during the entire cycle. There are three cases of system reliability in each cycle: *S*, *G*, and *U*. Each state has a certain probability of transformation between cycles. Fundamentally, the reliability evaluation of BIM-LSC System, based on Markov Chain, is to obtain the probability of system reliability state transition between the operating cycles, or the specific project phases in this context. Let matrix *P* represent the state transition probability matrix of the system,

$$\mathrm{P} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix} \tag{7}$$

Where, p_{11} is the probability that all the indicators belonging to *S* in the previous cycle of the system still belong to *S* after conversion to the next cycle,

$$p_{11} = \frac{S-S}{S'}; p_{12} = \frac{S-G}{S'}; p_{13} = \frac{S-U}{S'} \tag{8}$$

$$p_{11} + \ p_{12} + \ p_{13} = 1, p_{21} + \ p_{22} + p_{23} = 1,\ p_{31} + \ p_{32} + p_{33} = 1 \tag{9}$$

Where,

S-S means that the sum of the weights of indicators that belong to *S* in the previous cycle still belong to *S* after conversion to the next cycle;

S-G means that the sum of the weights of indicators that belong to *S* in the previous cycle, but belong to *G* after conversion to the next cycle;

S-U means that the sum of the weights of indicators that belong to *S* in the previous cycle, but belong to *U* after conversion to the next cycle;

S′ means that the sum of the weights of indicators that belong to *S* in the previous cycle.

Usually, as proved by the ergodicity of the Markov Chain, a system conforming to the law of Chapman–Kolmogorov equation will become stable with the progressive increase of the change period (*n*). Therefore, the state reliability evaluation value at time *t* will eventually reach a steady state after a change of multiple cycles. Considering the normalization conditions of the connection degree, the following equations can be used to obtain the BIM-LSC reliability evaluation steady-state prediction:

$$\begin{cases} a+b+c=1 \\ (a,b,c)\cdot(I-P)=0 \end{cases}. \tag{10}$$

Solving the equation will yield the prediction of the BIM-LSC reliability estimates of steady-state:

$$\mu = a+bi+cj, i\in[0,1], j=-1 \tag{11}$$

4 Result

The major innovation of the proposed reliability evaluation and prediction model resides in its ability in leveraging quantitative measures to not only evaluate the BIM-LSC reliability at a given state based on dynamics of the collection of reliability indicators, but also to predict the transition of such reliability when the states of the dynamic indicators change. Due to the lack of empirical project data on BIM-LSC reliability, empirical validation of the proposed model was not feasible. Instead, to demonstrate its application, a multi-cycle calculation was performed with indirect data inputs through the exploratory survey conducted among professionals with substantial project experience in both BIM and lean practices in China. The following provides the results of the calculation based on the hypothetical reliability scenarios.

4.1 Initial Values of Reliability Indicators

Using Equations (1 and 3), the calculations were performed using MATLAB software and summarized in Table 3 below. It should be noted that larger entropy weight coefficient values represent greater impacts on BIM-LSC Reliability.

Table 3. Entropy Weight Calculated for Each Reliability Evaluation Indicator

<< Insert Table 3 >>

4.2 BIM-LSC Reliability Evaluation

Based on the results of the entropy weight coefficient calculation, a Markov Chain simulation was run with four (4) cycles to define the *S*, *G*, and *U* sets that each indicator at each cycle belongs to, as shown in Table 4. For determining the appropriate number of simulation cycles, the research followed the recommendation made by Zhang (2012) and Zhang et al. (2016), which suggested extra cycles (more than 4) would not significantly improve the simulation results.

Table 4. Summary of BIM-LSC Reliability Evaluation Simulation Cycles

<< Insert Table 4 >>

The next step was to calculate the reliability evaluation connection degree of the BIM-LSC in Cycle 1 using Equations (1, 4, and 5). The calculation results are:

$$a = 0.519753, b = 0.18, c = 0.3$$

The same process was repeated for Cycles 2, 3, and 4, and the reliability evaluation connection degrees were obtained and shown below:

$$\mu_1 = 0.52 + 0.18i + 0.3j,\ \ \mu_2 = 0.24 + 0.58i + 0.18j,$$

$$\mu_3 = 0.60 + 0.28i + 0.12j, \ \ \mu_4 = 0.41 + 0.35i + 0.24j.$$

Taking μ_1 as an example, the above calculation results show that the identity degree of the set pair *H* including 17 evaluation indicators in Cycle 1 is 0.52, the discrepancy degree is 0.18, and the contrary degree is 0.3. According to the situations in table 2, the results indicated that in Cycle 1, the BIM-LSC reliability is Reliable, in Cycle 2 is Quasi-Reliable, in Cycle 3 is Reliable and in Cycle 4 is Reliable. The overall evaluation results suggested that the BIM-LSC reliability is between Reliable and Quasi-Reliable, and it fluctuated slightly in the process of dynamic transfer.

4.3 BIM-LSC Reliability Prediction

To predict the supply chain reliability connection degree, a State Transition Probability Matrix was calculated. From Cycle 1 to Cycle 2, some of the indicators that originally belong to S were converted into *S*, *G*, *U* sets. Then these indicators were synthesized to calculate the sum of weights of these converted indicators:

- *S* to *S*: 0.054847 + 0.055751 + 0.063074 = 0.173672;
- *S* to *G*: 0.058478 + 0.051284 + 0.054241 + 0.058365 = 0.222368;
- *S* to *U*: 0.057057 + 0.066656 = 0.123713.

Assuming the State Transition Matrix from Cycle 1 to Cycle 2 to be P_{12}, and according to Equations (7-9), the following values were calculated:

$$p_{11} = \frac{0.174}{0.52} = 0.335, p_{12} = \frac{0.222}{0.52} = 0.428, p_{13} = \frac{0.124}{0.52} = 0.237$$

Accordingly, the values of the remaining items in P_{12} can be determined as shown below:

$$P_{12} = \begin{bmatrix} 0.335 & 0.428 & 0.237 \\ 0.343 & 0.332 & 0.326 \\ 0 & 1 & 0 \end{bmatrix}$$

Similarly, assuming the *State Transition Matrix* from Cycle2 to Cycle 3 to be P_{23}, and the Cycle3 to Cycle 4 to be P_{34}, the matrices can be calculated as follows:

$$P_{23}=\begin{bmatrix} 0 & 0.743 & 0.257 \\ 0.813 & 0.093 & 0.094 \\ 0.968 & 0.032 & 0 \end{bmatrix}, \quad P_{34}=\begin{bmatrix} 0.401 & 0.296 & 0.302 \\ 0.428 & 0.3795 & 0.1925 \\ 0.45 & 0.55 & 0 \end{bmatrix}$$

Assuming that the weights of the *State Transition Probability* matrices of the respective periods are the same, according to P_{12}, P_{23},P_{34}, the average state transition probability matrix should be:

$$\mathrm{P}=\bar{P}=average\ \ (P_{12},P_{23},P_{34})$$

$$P=\begin{bmatrix} 0.245 & 0.49 & 0.265 \\ 0.528 & 0.268 & 0.204 \\ 0.473 & 0.527 & 0 \end{bmatrix}$$

Then, by applying $\boldsymbol{P}$ in Equation (10), where:

$$\begin{cases} a+b+c=1 \\ (a,b,c)\cdot\left(I-\begin{bmatrix} 0.245 & 0.49 & 0.265 \\ 0.528 & 0.268 & 0.204 \\ 0.473 & 0.527 & 0 \end{bmatrix}\right)=0 \end{cases}$$

The equation is fixed to: $\mathrm{a}=0.431, \mathrm{b}=0.468$, $\mathrm{c}=0.201$. Therefore, after the BIM-LSC reaches the stable state after Cycle 4, the following equation is valid:

$$\mu=0.431+0.468i+0.201j$$

According to Table 2, the predicted reliability status falls under Scenario 5, where *S* > *U*, *S* < *G*, and *G* > *U*, which suggests that the reliability of the BIM-LSC was quasi-reliable with minimal direct potential, and the overall reliability level tended to weaken. This indicates the importance for the project management team to focus their attention on controlling reliability, via measures such as the Set-Based Design, that can be realized through Lean and BIM-based procurement strategies to improve the overall supply chain reliability.

4.4 Semi-structure Interview

From the direct result of calculation, the result of Entropy weight provides an approach to improve the reliability of BIM-LSC. As “Set based design”, “Use Lean and BIM-based procurement”, “Asset tagging”, “Integrating FM system with BIM”, “Keep the maintenance model updated” had the highest weights in Table 3, project managers can start with these five links to improve the reliability of the supply chain efficiently.

In order to further analyze the results of EESM model calculation, the purposive sampling was employed to collect information on BIM-LSC reliability again. Thirty-four professionals with more than eight years of BIM experience were selected, and ten professionals participated in semi-structured interviews (see Appendix IV). Purposive sampling is a type of non-probability sampling that is most effective when one needs to study a certain cultural domain with knowledgeable experts within (Guarte and Barrios 2006, Warnecke et al. 1997). Each interview lasts about one hour. The interview outline is as follows:

1) What do you think of the current situation of BIM-LSC in the construction industry?

2) What do you think are the reasons for the quasi-reliable BIM-LSC?

3) What measures do you think can help improve the reliability of BIM-LSC?

The results of the interviews are sorted according to the questions, as shown in the Table 5.

Table 5. Results of semi-structured interviews

<< Insert Table 5 >>

5 Discussion

As for reliability evaluation and prediction, Cao and Li (2008) employed the Back-Propagation Neural network model to evaluate the reliability of the supply chain members where only 18 sample data were collected. Pan et al. (2011) adopted “SIMPROCESS” computer simulation software to explore the behavior of the construction supply chain in dynamic situation, but there is no innovation in the math calculation method. Liu et al. (2009) applied Markov chain theory to study the information flow response time distribution of south-to-north water diversion supply chain in China, which did not consider the reliability characteristic. This paper collected 316 valid questionnaires and proposed EESM to evaluate the reliability of the supply chain in an uncertain environment. To calculate the index weight of supply chain reliability, Deng et al. (2016) established the Triangular fuzzy analytic hierarchy process, which overcomes the shortcomings of traditional weight calculation. While in EESM, the more objective entropy method was applied to determine the weighting factor of the reliability indicators and SPA was applied to describe the degrees of connection between indicators in BIM-LSC. The EESM model for reliability evaluation and prediction can enhance BIM-LSC management, leading to an improved project performance. Unlike previous research that has typically focused on performing static reliability assessment of supply chains (during a certain period of time with a specific set of project conditions), this research has responded to the need to consider uncertainty factors in complex business environments, where the reliability status of the supply chain may change dynamically.

The demonstrated calculations of EESM model provide evidences of the practicality of the proposed approach and this proposed a platform for future research to build upon in implementing an integrated approach for BIM-LSC reliability evaluation and prediction. Based on these results, it is possible to perform the calculation to be replicated with ease, and the interpreted results support the potential to uncover relatively complex dynamics among reliability indicators via quantitative information. This integrated BIM-LSC reliability evaluation and prediction approach offers an alternative method that could provide greater confidence to project teams in BIM-LSC management, especially when traditional models struggle to accurately respond uncertainty factors and unforeseen project conditions.

The result calculated the reliability of BIM-LSC was quasi-reliable. By purposive sampling, the development of BIM-LSC is closely related to the promotion of BIM technology. This is in parallel with the study of Aziz and Arayici (2018) that the application of BIM in large-scale construction project enabled to gain lean efficiencies. In addition, lean concepts as new management thinking have suggested a better maintenance process by improving the reliability of delivery workflows. These results are generally in line with the literature (Wenchi et al. 2014, Mahalingam et al. 2015).

Nevertheless, as an exploratory work, there are limitations that may affect the accuracy and validity of the proposed model in real-world scenarios and are recommended to be addressed in future research. Firstly, due to the absence of an existing index system with clearly defined indicators for BIM-LSC reliability evaluation, this research adopted the BIM-Lean workflow functions from the authoritative CIRIA C725 Lean and BIM Guide and relied solely on the five primary and 17 secondary indicators. Although these indicators are supported by both industry and academic literature, it is inevitably limited for use in developing a specific reliability evaluation index system using this approach. This is due to the generalist nature of the indicators (both primary and secondary) and the lack of specificity when applied to describe the BIM-LSC performance in a given project context. Secondly, although the relationship between BIM-LSC has been well-observed by construction project teams, limited information is available on supply chain reliability during the project delivery process. In addition, representative supply chain performance data should be collected for reliability evaluation and prediction purposes. This research validated and evaluated the proposed model using project information to a limited extent. Therefore, future research opportunities exist to validate the relationships between conventional KPIs and supply chain reliability and to improve the potential application of the proposed model.

6 Conclusions

The research on BIM-LSC reliability evaluation and prediction presented in this paper provides a strong theoretical foundation to enhanced understanding of the BIM-LSC in a construction project context. By proposing the EESM model, this study adopted 17 indicators from CIRIA C725 Lean and BIM Guidebook and obtained 316 valid questionnaires to calculate the reliability in an uncertain environment. The calculation suggested that the overall reliability level of BIM-LSC tended to weaken.

The three major contributions of the research are: 1) elaborating the workflow of BIM-LSC and provided the guidelines for implementation; 2) supporting the critical role of reliability to BIM-LSC performance and the development of an index system for its reliability evaluation and prediction; and 3) justifying in the application of the entropy method, SPA theory and Markov Chain process to be integrated in the evaluation and prediction of BIM-LSC reliability. The results indicate that the proposed BIM-LSC model can handle not only supply chain reliability evaluation at a given state, but also the prediction of reliability in supply chain state transitions due to changing project conditions. This is particularly relevant in current project environments that are characterized by the increased complexity of labor, technology and resources interactions.

Future research opportunities exist to: 1) further develop the accuracy of BIM-LSC reliability evaluation index system by triangulating both quantitative (e.g. surveys questionnaires) and qualitative (e.g. content analysis of project management documentation) data; and 2) empirically test the refined BIM-LSC reliability model in real-world settings (e.g. capital project case studies) across the entire lifecycle to validate and possibly strengthen its predictive power.

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