

1 **To cite this paper:**

2 Zhang, J.\*, Li, H., Golizadeh, H., Zhao, C., Lv, S., and Jin, R. (2019). “Reliability Evaluation  
3 Index for the Integrated Supply Chain Utilizing BIM and Lean Approaches.” *Engineering,  
4 Construction and Architectural Management*, DOI: 10.1108/ECAM-12-2018-0542

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

6 **Approaches**

7 **Abstract**

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

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

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

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

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

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

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

35 **Article Type:** Research Paper.

## 36 **1 Introduction**

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

46           Recently, emerging approaches including Building Information Modeling (BIM), Lean  
47 Construction and Green Building methods are reshaping the global business environment of the  
48 construction industry (Zuo et al. 2017, Zuo and Zhao 2014, Ding et al. 2015). Best practices in  
49 adoption and implementation of these applications have shed light on the strategies to reduce  
50 waste, improve productivity, promote performance and maximize added value and profitability  
51 through a project's life cycle (Ahuja, Sawhney and Arif 2017). The integrated BIM-Lean  
52 Supply Chain (BIM-LSC) concept is gradually gaining recognition by the industry (Dave et al.  
53 2013, Sacks et al. 2010). As a synergistic convergence of technological advancement and  
54 business process improvement, BIM-LSC has been applied to holistically and strategically  
55 address socioeconomic and environmental sustainability goals (usually defined as the triple-  
56 bottom-line) and help accomplish green project outcomes (Fernández-Solís and Mutis 2010,  
57 Ahuja et al. 2017, Wu and Issa 2015, Ahuja et al. 2014).

58           To elaborate on BIM-LSC interaction, BIM serves as the technological and  
59 communication platform for related project life-cycle information to be generated, exchanged,  
60 managed and shared among project stakeholders with stipulated roles and responsibilities,  
61 under specific contractual protocols (Hjelseth et al. 2010). By eliminating information silos and  
62 avoiding communication gaps, BIM offers a reliable, flexible and functional foundation to more  
63 streamlined business processes and efficient project execution, which can eventually lead to  
64 waste reduction, time and budget savings, improved profitability and client satisfaction (Azhar  
65 2011, Bryde, Broquetas and Volm 2013). Nevertheless, to fully exploit the benefits of BIM,  
66 human behaviors play an essential role rather than technology (Smith and Tardif 2009,  
67 Fernández-Solís and Mutis 2010). In addition, originated from the automobile and

68 manufacturing industry, lean principles can provide project teams with the desired mechanism  
69 to deploy, manage, monitor successful BIM project platform execution, and drive more efficient  
70 utilization of resources and energy to achieve sustainability performance and goals (Sacks et al.  
71 2010, Ahuja et al. 2017, Khodeir and Othman 2016, Ahuja et al. 2014). In this paper, BIM-LSC  
72 refers to the synergistic use of BIM technology and Lean principles in the construction supply  
73 chain in order to enhance information-driven collaboration capabilities of project teams so that  
74 business process performance can be improved in delivering capital projects.

75 BIM-SLC has gained wide attention. These include general discussion and  
76 documentation of the BIM-Lean interaction evidence (e.g. Sacks et al. 2010), detailed analysis  
77 and delineation of the interactive matrix and dynamics (e.g. Bin, Bo-sheng and You-qun 2011),  
78 and identification of enablers, methods, tools and strategies to facilitate its integration and  
79 measuring its maturity (e.g. Dave et al. 2013). Nevertheless, despite the plethora of available  
80 tools, the evaluation of *reliability* as a major success factor in SCM has not been investigated  
81 in the context of BIM-LSC. Time, budget and quality are typical constraints in project  
82 management (Ford and Bhargav 2006). **Therefore, this paper defines BIM-LSC reliability**  
83 **as “the ability to deliver a capital project with a specified time, budget and quality**  
84 **conditions, under the influence of a variety of uncertainty factors, to deliver green**  
85 **outcomes using the lean production process and BIM technology”**. In line with the temporal  
86 nature of construction projects, project-based BIM-LSC faces challenges of instability,  
87 fragmentation, and the disjointedness between project design and construction as inherent  
88 characteristics of construction projects. At the same time, BIM-LSC focuses on multi-stage  
89 production and multi-stakeholder. The nature of this phenomenon emphasizes the need for high

90 reliability in supply chain interaction to reduce uncertainty. As the supply chain hierarchy in  
91 contemporary construction projects becomes increasingly complex, uncertainty factors can  
92 severely and adversely affect the normal operation of the supply chain, which necessitates better  
93 understanding, evaluation, and prediction of its reliability (Mahnam et al. 2009).

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

## 106 **2 Literature Review**

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

110

<<

Insert Figure 1

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111

112 ***2.1 BIM and Lean Supply Chain***

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

119 Previous studies on BIM-LSC have focused on new business processes that are driven by  
120 rapid BIM adoption and implementation, and the desired transition of contractual relationship  
121 and partnership among project stakeholders. Due to the dynamic interaction and synergistic  
122 convergence of BIM and Lean (Sacks et al. 2010), BIM-LSC features the unprecedented use of  
123 information technology and critical needs for the project information management (Dave et al.  
124 2013). Thus, BIM-LSC is data-intensive and information-centric (Tommelein, Ballard and  
125 Kaminsky 2008). The integration of these concepts has been studied extensively. For example,  
126 the process of prefabrication housing production from manufacturing and logistics to the on-  
127 site assembly by integrating the BIM platform with lean construction has been simulated.  
128 Furthermore, Irizarry et al. (2013) combined BIM technology with geographic information  
129 system (GIS) to construct a visualization model of the material supply chain to perform model-  
130 based material takeoff. Using the reinforced concrete supply chain as a case study, Aram et al.  
131 (2012, 2013) demonstrated that BIM technology could significantly improve construction  
132 supply chain efficiency via automation and fluency of its information exchange. Yu, Lv and

133 Zhang (2016) proposed a roadmap of applying BIM technology for improved construction  
134 SCM and established a BIM-based SCM information system framework. Wen, Wang and Xia  
135 (2009) proposed to build a lean construction supply chain model with modular thinking to  
136 improve the transparency of information in the supply chain. Further, Dave et al. (2013)  
137 acknowledged that high synergistic effect between BIM technology and Lean, and proposed a  
138 systematic strategy to adopt BIM-LSC to ensure that information is effectively synergized  
139 throughout the project lifecycle.

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

144 << Insert Figure 2 >>

145 Fig. 2. BIM and Lean Workflow

146 *Note:* This workflow is in line with Table 1.

## 147 ***2.2 Project-based BIM-LSC Reliability Evaluation Index System***

148 Supply chain reliability provides a theoretical background to quantify supply chain risks and  
149 uncertainties (Ha et al. 2018). Thomas (2002) first introduced the engineering reliability theory  
150 in SCM and defined the supply chain reliability as “the ability to complete a given task at a  
151 specified time and other conditions”. Liu and Luo (2007) considered the supply chain  
152 operations reference model and defined supply chain reliability from the enterprise perspective  
153 as the ability of the supply chain to achieve normal operations for a period. Mu (2010)  
154 approached the problem from a complexity theory position and defined reliability as the

155 likelihood of meeting customer needs at the time, quantity, and quality required by the end  
156 customer. Similar studies on the scope of reliability and reliability evaluation include Zhao and  
157 Yang (2007) and Zhang (2012). Therefore, this paper defined the reliability in BIM and lean  
158 background as “the ability to deliver a capital project with a specified time, budget and quality  
159 conditions, under the influence of a variety of uncertainty factors, to deliver green outcomes  
160 using the lean production process and BIM technology”.

161         Currently, there are limited studies that have assessed the reliability of BIM and Lean  
162 integrated supply chains, so the relevant reliability evaluation index system needs to be  
163 developed. The UK Construction industry research and information association (CIRIA) links  
164 organizations with common interests and facilitates a range of collaborative activities that help  
165 improve the industry. CIRIA published the CIRIA C725 Lean and BIM Guidebook (Dave et al.  
166 2013): *Implementing lean in construction: lean construction and BIM*. This guide was  
167 submitted to the British government and represented accurate and authoritative information on  
168 the joint application of Lean and BIM. It was the first of its kind and compiled both academic  
169 and professional knowledge incorporated in its development, and it articulated the main tools  
170 and techniques that are applied in Lean and BIM projects.

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

175 Table 1. Proposed BIM-LSC Reliability Evaluation Index System

176

<<

Insert Table 1

>>



### 177 *2.3 Supply Chain Reliability Evaluation and Prediction model*

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

198            However, the method to calculate the reliability in an uncertain environment is limited.

199    This limitation hinders the promotion of BIM and lean approach in the construction industry.

#### 200    **2.4 Knowledge Gap**

201    The synergies of BIM and Lean has gained an increasingly level of recognition. However, there

202    are very limited studies on BIM-LSC reliability evaluation and prediction. These existing

203    studies predominantly focused on the static assessment of reliability status at a certain period

204    of time to identify safety levels, with less focuses on future reliability states and its dynamic

205    trends (Peng et al. 2017, Zhang et al. 2016). Little attention has been paid to the measurement

206    roles of information (entropy) in the reliability evaluation (Short and Wehner 2010).

207    Information is a key measurement indicator for the degree of systematic ordering, and entropy

208    is a measurement of the degree of system disorder. BIM-LSC, as a highly integrated information

209    chain, can significantly benefit from the use the entropy method to measure the amount of BIM

210    information provided by the BIM-LSC indicators. This assists in targeting the evaluation of

211    BIM-LSC reliability and provides the precise prediction. Meanwhile, current methods

212    experience difficulties in the quantitative analysis and prediction of the stability of BIM supply

213    chain under uncertain environment. In order to predict the reliability of the supply chain, it is

214    necessary to consider the orderly state transfer between nodes in the supply chain.

215            This research attempts to address this gap. Motivated by this imperative need to measure

216    and respond to BIM-LSC reliability, this research reviewed and identified key reliability

217    indicators for BIM-LSC, and adopted an integrated approach to develop a BIM-LSC reliability

218    evaluation model. The proposed model relied on the entropy method to determine the weighting

219    factor of the reliability indicators, and SPA to describe the degrees of connection between

220 indicators in BIM-LSC. Finally, the Markov chain process was employed to predict reliability  
221 transitions when the status of individual indicators and their dynamics had changed. To  
222 demonstrate the potential application of the proposed model, a multi-cycle calculation was  
223 performed with indirect data inputs through an exploratory survey.

### 224 **3 Methodology**

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

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

244 << Insert Figure 3 >>

245 Fig. 3. EESM model

### 246 ***3.1 Expert Survey to Scale the Project-Based BIM-LSC Reliability Evaluation***

#### 247 ***Index***

248 To test the model, the first step was to apply the entropy method for reliability indicators'  
249 weight coefficients calculation. The initial values of the five sets and a total of 17 BIM-LSC  
250 Reliability evaluation indicators were assigned. As stated, there is currently a lack of first-hand  
251 BIM-Lean project information. This research used an alternative approach by collecting subject  
252 matter experts' perception values of these indicators using a survey questionnaire to capture the  
253 "*BIM-LSC Reliability Impact Factor*", and conducted a comprehensive online and offline  
254 (paper-based) survey with a convenient sample to industry professional, project managers or  
255 consultants who have at least three years of experience in BIM-based projects. For each of these  
256 17 indicators, the participants were requested to rate each factor's impact on BIM-LSC  
257 reliability on a 5-point Likert-type scale, where "1" was for No impact, "2" for Minor impact,  
258 "3" for Neutral, "4" for Moderate impact and "5" for Major impact. A total of 600 online/offline  
259 questionnaires were distributed and 338 completed questionnaires were collected, with a  
260 response rate at 56.3%. Prior to data analysis, data screening was implemented to inspect data  
261 for errors that involves checking raw data and identifying outliers. Eventually, a total of 316  
262 valid datasets were obtained (see Appendix I). The mean values of the Likert scale impact factor

263 ratings were then assigned to the 17 indicators as their initial values for the weight coefficient  
264 calculation with the entropy method.

### 265 ***3.2 Entropy Method to Calculate the Index Weight of Project-Based BIM-LSC***

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

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

### 281 ***3.3 SPA to Determine the Degrees of Connection as Expression of the Reliability***

#### 282 ***Levels***

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

285 2003). Therefore, it is sensible that this paper adopted SPA to analyze the reliability of the  
286 supply chain under the uncertain environment. Meanwhile, this paper simulated the supply  
287 chain with Markov chain and simulated the supply chain service process with Markov chain  
288 node state transition, which fully reflected the dynamics of the supply chain and made the  
289 prediction closer to reality. The combination of the two methods solved the dilemma of  
290 quantitative analysis of previous research methods and improved the accuracy of BIM supply  
291 chain reliability analysis and prediction under uncertain environment.

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

296 Given two sets  $\mathcal{V}$  and  $\mathcal{U}$ , the set pair is expressed as  $H = (\mathcal{V}, \mathcal{U})$ . Equation (1) calculates  
297 the connection degree of the two sets:

$$298 \quad \mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj, \text{ where } a + b + c = 1 \quad (1)$$

### 299 **3.4 Markov Chain Model to Build States Transition Probability Matrix**

300 The supply chain is an extremely complex system with fuzzy and rough information, which has  
301 significant uncertainties (Ebrahimi et al. 2011). Meanwhile, the supply chain is composed of  
302 many enterprise nodes. The operation of the supply chain requires enterprise nodes to update  
303 their status constantly and orderly so that the supply chain has obvious dynamics (Towill 2003,  
304 Towill 1982). The status of the supply service is either reliable or unreliable, while it may shift  
305 during a certain period. Moreover, the status of the service provided in each period is only  
306 related to the status of each operation link of the supply service in that time and is independent

307 on the supply service before the period. The randomness and aftereffect less match the  
 308 requirement of the Markov chain. Therefore, this paper adopted Markov chain to simulate the  
 309 supply chain and realizes the dynamic prediction of the reliability of the supply chain. It is more  
 310 dynamic and more realistic than the general static methods used in the previous studies.

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

314 Reliability = The probability that the system will complete the supply task on time  
 315 = 1 - The probability that the system will not complete the supply task on time  
 316 = 1 - (Failure Rate - Maintenance rate × Failure Rate)

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

324 Given  $E$  is the probability space, and  $\{C(n), n \geq 0\}$  is an integer random sequence defined  
 325 in the probabilistic space. If  $m \geq 1$ ,  $C(t_1), C(t_2), \dots, C(t_m)$  corresponding to  $C(n)$  for  $t_1, t_2, \dots,$   
 326  $t_m$  (where  $t_1 < t_2 < \dots < t_m$ ) ( $t_m$ ) meet the conditions:

327 
$$P(C(t_m)) | C(t_m - 1), C(t_m - 2), \dots, C(t_1)) = P(C(t_m)) | C(t_m - 1) \quad (2)$$

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

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

### 332 **3.5 A New Approach for BIM-Lean Supply Chain Reliability**

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

#### 335 **3.5.1 Weight Calculation of Evaluation Indicators Based on the Entropy Method**

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

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

$$342 \quad W = (\omega_t)_{1 \times n}, \omega_t = (1 - H_t) / (n - \sum_{t=1}^n H_t) \text{ with } \sum_{t=1}^n \omega_t = 1 \quad (3)$$

#### 343 **3.5.2 SPA-based Reliability Evaluation Model**

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



350 
$$S + G + U = 1 \tag{4}$$

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

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

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

366 
$$\begin{aligned} \mu &= a + bi + cj \\ &= \sum_{k \in S} \omega_k + \sum_{k \in G} \omega_k \cdot i + \sum_{k \in U} \omega_k \cdot j \end{aligned} \tag{5}$$

367 Where,

368 
$$a = \sum_{k \in S} \omega_k, b = \sum_{k \in G} \omega_k \cdot i, c = \sum_{k \in U} \omega_k \cdot j \tag{6}$$

369 It should be noted that  $\omega_k$  refers to the weight of reliability index, which is generated by  
 370 Equation (10). Let  $i = 0, j = -1$ , then the reliability Connection Degree  $\mu \in [-1, 1]$ . According  
 371 to the average principle, the values of  $\mu$  represent corresponding reliability levels. In other

372 words,  $-1 \leq \mu \leq -0.333$  designates as *unreliable* or *U*, while  $-0.333 < \mu < 0.333$  designates as  
373 *quasi-reliable* or *G*, and  $0.333 \leq \mu \leq 1$  designates as *reliable* or *S*.

374 To further explain the system dynamics of BIM-LSC and elaborate on the possible  
375 reliability level variation of each indicator within the established reliability index system, Table  
376 2 summarized the possible set pair potentials conditioned on comparisons of the sizes of  
377 indicators with the specific reliability levels, i.e. *S*, *G* or *U*, as suggested by Zhang (2012) and  
378 Zhang et al. (2016). The primary comparison was made between the sizes of *S* indicators and  
379 *U* indicators. Specifically, if the size of *S* indicators > size of *U* indicators, the set pair potential  
380 is considered to be “*Direct*”; otherwise, if the size of *S* indicators = size of *U* indicators, the set  
381 pair potential is “*Balanced*”; and finally, if the size of *S* indicators < size of *U* indicators, the  
382 set pair potential is “*Inverse*”. Under each of the three primary set pair potential groups, two  
383 additional secondary comparisons were made between the sizes of *S* and *G* indicators, and the  
384 sizes of *U* and *G* indicators, respectively, which yielded further granularity of set pair potentials,  
385 as shown in Table 3. As a result, a total of 13 different set pair situation scenarios were recorded,  
386 which corresponded with a particular outcome of the BIM-LSC reliability. Based on these  
387 evaluation results, the project team can take the corresponding preventive measures to reduce  
388 and avoid the risk of potential BIM-LSC failures.

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

390 << Insert Table 2 >>

### 391 3.5.3 Markov Chain-based Reliability Prediction Model

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

$$400 \quad P = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix} \quad (7)$$

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

$$403 \quad p_{11} = \frac{S-S}{S'}; p_{12} = \frac{S-G}{S'}; p_{13} = \frac{S-U}{S'} \quad (8)$$

$$404 \quad p_{11} + p_{12} + p_{13} = 1, p_{21} + p_{22} + p_{23} = 1, p_{31} + p_{32} + p_{33} = 1 \quad (9)$$

405 Where,

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

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

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

412  $S'$  means that the sum of the weights of indicators that belong to  $S$  in the previous cycle.

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

$$419 \quad \begin{cases} a + b + c = 1 \\ (a, b, c) \cdot (I - P) = 0 \end{cases} \quad (10)$$

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

$$422 \quad \mu = a + bi + cj, i \in [0, 1], j = -1 \quad (11)$$

#### 423 **4 Result**

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

433 **4.1 Initial Values of Reliability Indicators**

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

437 Table 3. Entropy Weight Calculated for Each Reliability Evaluation Indicator

438 << Insert Table 3 >>

439 **4.2 BIM-LSC Reliability Evaluation**

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

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

447 << Insert Table 4 >>

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

450 
$$a = 0.519753, b = 0.18, c = 0.3$$

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

453 
$$\mu_1 = 0.52 + 0.18i + 0.3j, \mu_2 = 0.24 + 0.58i + 0.18j,$$

454 
$$\mu_3 = 0.60 + 0.28i + 0.12j, \mu_4 = 0.41 + 0.35i + 0.24j.$$

455 Taking  $\mu_1$  as an example, the above calculation results show that the identity degree of the  
 456 set pair  $H$  including 17 evaluation indicators in Cycle 1 is 0.52, the discrepancy degree is 0.18,  
 457 and the contrary degree is 0.3. According to the situations in table 2, the results indicated that  
 458 in Cycle 1, the BIM-LSC reliability is Reliable, in Cycle 2 is Quasi-Reliable, in Cycle 3 is  
 459 Reliable and in Cycle 4 is Reliable. The overall evaluation results suggested that the BIM-LSC  
 460 reliability is between Reliable and Quasi-Reliable, and it fluctuated slightly in the process of  
 461 dynamic transfer.

462 **4.3 BIM-LSC Reliability Prediction**

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

- 467 •  $S$  to  $S$ :  $0.054847 + 0.055751 + 0.063074 = 0.173672$ ;
- 468 •  $S$  to  $G$ :  $0.058478 + 0.051284 + 0.054241 + 0.058365 = 0.222368$ ;
- 469 •  $S$  to  $U$ :  $0.057057 + 0.066656 = 0.123713$ .

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

472 
$$p_{11} = \frac{0.174}{0.52} = 0.335, p_{12} = \frac{0.222}{0.52} = 0.428, p_{13} = \frac{0.124}{0.52} = 0.237$$

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

474 
$$P_{12} = \begin{bmatrix} 0.335 & 0.428 & 0.237 \\ 0.343 & 0.332 & 0.326 \\ 0 & 1 & 0 \end{bmatrix}$$

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

$$477 \quad P_{23} = \begin{bmatrix} 0 & 0.743 & 0.257 \\ 0.813 & 0.093 & 0.094 \\ 0.968 & 0.032 & 0 \end{bmatrix}, \quad P_{34} = \begin{bmatrix} 0.401 & 0.296 & 0.302 \\ 0.428 & 0.3795 & 0.1925 \\ 0.45 & 0.55 & 0 \end{bmatrix}$$

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

$$481 \quad P = \bar{P} = \text{average} (P_{12}, P_{23}, P_{34})$$

$$482 \quad P = \begin{bmatrix} 0.245 & 0.49 & 0.265 \\ 0.528 & 0.268 & 0.204 \\ 0.473 & 0.527 & 0 \end{bmatrix}$$

483 Then, by applying  $P$  in Equation (10), where:

$$484 \quad \begin{cases} a + b + c = 1 \\ (a, b, c) \cdot \left( I - \begin{bmatrix} 0.245 & 0.49 & 0.265 \\ 0.528 & 0.268 & 0.204 \\ 0.473 & 0.527 & 0 \end{bmatrix} \right) = 0 \end{cases}$$

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

$$487 \quad \mu = 0.431 + 0.468i + 0.201j$$

488 According to Table 2, the predicted reliability status falls under Scenario 5, where  $S > U$ ,  
 489  $S < G$ , and  $G > U$ , which suggests that the reliability of the BIM-LSC was quasi-reliable with  
 490 minimal direct potential, and the overall reliability level tended to weaken. This indicates the  
 491 importance for the project management team to focus their attention on controlling reliability,

492 via measures such as the Set-Based Design, that can be realized through Lean and BIM-based  
493 procurement strategies to improve the overall supply chain reliability.

#### 494 ***4.4 Semi-structure Interview***

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

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

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

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

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

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

511 5.

512 Table 5. Results of semi-structured interviews

513 << Insert Table 5 >>



514 **5 Discussion**

515 As for reliability evaluation and prediction, Cao and Li (2008) employed the Back-Propagation  
516 Neural network model to evaluate the reliability of the supply chain members where only 18  
517 sample data were collected. Pan et al. (2011) adopted “SIMPROCESS” computer simulation  
518 software to explore the behavior of the construction supply chain in dynamic situation, but there  
519 is no innovation in the math calculation method. Liu et al. (2009) applied Markov chain theory  
520 to study the information flow response time distribution of south-to-north water diversion  
521 supply chain in China, which did not consider the reliability characteristic. This paper collected  
522 316 valid questionnaires and proposed EESM to evaluate the reliability of the supply chain in  
523 an uncertain environment. To calculate the index weight of supply chain reliability, Deng et al.  
524 (2016) established the Triangular fuzzy analytic hierarchy process, which overcomes the  
525 shortcomings of traditional weight calculation. While in EESM, the more objective entropy  
526 method was applied to determine the weighting factor of the reliability indicators and SPA was  
527 applied to describe the degrees of connection between indicators in BIM-LSC. The EESM  
528 model for reliability evaluation and prediction can enhance BIM-LSC management, leading to  
529 an improved project performance. Unlike previous research that has typically focused on  
530 performing static reliability assessment of supply chains (during a certain period of time with a  
531 specific set of project conditions), this research has responded to the need to consider  
532 uncertainty factors in complex business environments, where the reliability status of the supply  
533 chain may change dynamically.

534 The demonstrated calculations of EESM model provide evidences of the practicality of the  
535 proposed approach and this proposed a platform for future research to build upon in

536 implementing an integrated approach for BIM-LSC reliability evaluation and prediction. Based  
537 on these results, it is possible to perform the calculation to be replicated with ease, and the  
538 interpreted results support the potential to uncover relatively complex dynamics among  
539 reliability indicators via quantitative information. This integrated BIM-LSC reliability  
540 evaluation and prediction approach offers an alternative method that could provide greater  
541 confidence to project teams in BIM-LSC management, especially when traditional models  
542 struggle to accurately respond uncertainty factors and unforeseen project conditions.

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

550 Nevertheless, as an exploratory work, there are limitations that may affect the accuracy  
551 and validity of the proposed model in real-world scenarios and are recommended to be  
552 addressed in future research. Firstly, due to the absence of an existing index system with clearly  
553 defined indicators for BIM-LSC reliability evaluation, this research adopted the BIM-Lean  
554 workflow functions from the authoritative CIRIA C725 Lean and BIM Guide and relied solely  
555 on the five primary and 17 secondary indicators. Although these indicators are supported by  
556 both industry and academic literature, it is inevitably limited for use in developing a specific  
557 reliability evaluation index system using this approach. This is due to the generalist nature of

558 the indicators (both primary and secondary) and the lack of specificity when applied to describe  
559 the BIM-LSC performance in a given project context. Secondly, although the relationship  
560 between BIM-LSC has been well-observed by construction project teams, limited information  
561 is available on supply chain reliability during the project delivery process. In addition,  
562 representative supply chain performance data should be collected for reliability evaluation and  
563 prediction purposes. This research validated and evaluated the proposed model using project  
564 information to a limited extent. Therefore, future research opportunities exist to validate the  
565 relationships between conventional KPIs and supply chain reliability and to improve the  
566 potential application of the proposed model.

## 567 **6 Conclusions**

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

574 The three major contributions of the research are: 1) elaborating the workflow of BIM-  
575 LSC and provided the guidelines for implementation; 2) supporting the critical role of reliability  
576 to BIM-LSC performance and the development of an index system for its reliability evaluation  
577 and prediction; and 3) justifying in the application of the entropy method, SPA theory and  
578 Markov Chain process to be integrated in the evaluation and prediction of BIM-LSC reliability.  
579 The results indicate that the proposed BIM-LSC model can handle not only supply chain

580 reliability evaluation at a given state, but also the prediction of reliability in supply chain state  
581 transitions due to changing project conditions. This is particularly relevant in current project  
582 environments that are characterized by the increased complexity of labor, technology and  
583 resources interactions.

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

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