A model of BIM application capability evaluation for Chinese construction enterprises based on interval grey clustering analysis

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1. Introduction

In recent years, Building Information Modeling (BIM) has experienced a rapid development in China (Wu et al. 2017) and become more common application in construction projects (Lin and Yang 2018). As the second revolution in the Architecture, Engineering and Construction (AEC) industry, Building Information Modeling (BIM) has been considered to be the most promising recent developments (Lin, Lee, and Yang 2016) as well as the leading technology for use in AEC practices (Ghaffarian-Hoseini et al. 2017). It has a critical role in enhancing the effectiveness of project delivery from the initial concept to completion and post-construction maintenance (Ding, Zhou, and Akinci 2014; Volk, Stengel, and Schultmann 2014), and also has a significant impact on the efficiency of generation of building information and sharing of this information among various stakeholders throughout the building lifecycle (Yilmaz, Akcamete-Gungo, and Demirors 2017).

According to a survey by China in 2019, 52.07% of construction enterprises were engaged with BIM on less than 10 projects, while only 7.03% of construction enterprises were engaged with BIM on more than 50 projects (Chen et al. 2019). Furthermore, there were still 18.09% of construction enterprises which have not established a BIM organization, not to mention continuous BIM usages. These imply that although BIM is in a stage of rapid development in China, the BIM application capability is as a whole insufficient. BIM application capability is the comprehensive one involving the management, technology and human in the process of introducing and applying BIM in the enterprise (Wang and Li 2018). The challenge is how to improve the BIM adoption rate and application capability of China. To address this challenge, an assessment schema for AEC organizations should be developed to gauge the effectiveness of BIM implementations in order to measure the performance of BIM utilizations and enable continuous BIM improvements (Yilmaz, Akcamete, and Demirors 2019). However, there is not enough emphasis on the issue in China. Only a few studies have focused on the evaluation of BIM application capability (Wang et al. 2017; Yu 2017; Wang and Li 2018).

In addition, in order to make a quantitative evaluation of BIM application capability, an appropriate evaluation method should be found. This study introduced interval grey clustering analysis (IGCA) for the evaluation of BIM application capability. Considering that there are few studies on BIM application capability evaluation, this study established an IGCA-based evaluation model of BIM application capability, which included evaluation index system, BIM application capability levels and quantitative assessment method. The model could provide theoretical and practical guidance for evaluating and improving BIM application capability of AEC enterprises.
2. Literature review

Successful BIM implementation requires a thorough understanding of the current situation of BIM operations as well as effective, advanced, and high-performing measurements (Wu et al. 2017). However, there is not enough emphasis on the issues in China. Wang et al. (2017) and Yu (2017) established the index system for BIM application capability evaluation and conducted the assessment based on the analytic hierarchy process (AHP). Wang and Li (2018) utilized the factor analysis to construct an index system for enterprise BIM application capability evaluation, but there was no quantitative evaluation. In addition, the established index systems were not comprehensive, and the classification and hierarchy were confusing: divisions or sub-divisions with the same title comprised different measures. For instance, the measure “BIM related training” was classified under the organizational aspect in Wang et al. (2017), while this measure was under the process aspect in Yu (2017). These differences easily lead to confusions. In fact, this measure is generally classified under Human aspect (Succar 2010).

Considering that there are few studies on BIM application capability evaluation in China, the BIM maturity model can serve as a reference for the development of BIM application capability evaluation model due to the similarities and overlaps between the metrics of the two (Wang and Li 2018). Several models have been developed abroad to measure BIM maturity, such as NBIMS CMM (NIBS, 2007), BIM PM created by Indiana University Architect’s Office (IU Architect’s Office, 2009), BIM QuickScan from the Netherlands (Van Berlo and Hendriks 2012), VDC Scorecard developed by Stanford University Center for Integrated Facility Engineering (Kam et al. 2013) and BIM MM by (Succar 2010). NBIMS CMM was proposed by the National Institute of Building Science in 2007. The model evaluates BIM implementation in 11 areas using a 10-level scale (NIBS 2007; Giel 2014). It focuses on evaluating BIM maturity of construction projects. BIM PM was designed to assess BIM services performance in terms of 8 areas, 32 measures and 5 maturity levels (CIC 2012). Unlike NBIMS CMM, it focuses on assessing the BIM maturity of organizations. Although the two models are the bases for the following models, they are usually criticized because of limited measurement scope in technical aspects (Succar 2010). BIM MM was developed to assess BIM performance of organizations, projects, teams and individuals. It provides comprehensive explanations for each measure to minimize inconsistencies and expands the measuring scope to cover non-technical aspects of BIM (Giel and Issa 2013). BIM QuickScan was launched in 2011. It consists of 4 main areas and 44 measures, which provides insight into the strengths and weaknesses of BIM usage in an organization. VDC Scorecard was developed in 2012 by Stanford University. It measures the project performance against an industry benchmark, which includes 4 main areas, 10 divisions, and 74 measures (Kam et al. 2013). Although each model has a different number of measures clustered into different numbers of layers, the common concepts have been selected to define the metrics. In most models, their measures are classified into the common categories, which are process, stakeholder/personnel, standard, software, hardware, and data (Yilmaz, Akcamete, and Demirors 2019). Moreover, according to Chinese researches Wang and Li (2018), BIM application capability is the comprehensive one involving the management, technology and human in the process of introducing and applying BIM in the enterprise. Therefore, based on the above research, we classified BIM application capability into three dimensions: technology, organization and management, and human aspect.

In terms of research methods of BIM application capability evaluation, most literatures utilized analytic hierarchy process (AHP) for evaluation (Wang et al. 2017; Yu 2017). Although AHP is a common method to solve multicriteria decision-making (MCDM) problems, the results obtained through it tend to be subjective. Moreover, capability assessment is affected by many factors, and most of these factors are qualitative measures, which makes it difficult to conduct quantitative evaluation when the information is uncertain and incomplete. Grey system theory is a method to handle uncertainties in small data samples with imprecise information (Wong and Hu 2013; Sun, Liang, and Wang 2019). Grey clustering analysis is one of the classic methods of grey evaluation methods. It is the combination of grey system theory and cluster analysis, and is widely utilized in many fields such as economics, military, biology, transportation and environmental quality assessment (Yuan and Liu 2012; Pei and Wang 2013; Xie, Liu, and Zhan 2013; Jian et al. 2014; Shen, Xu, and Wang 2008; Wang, Ning, and Chen 2012; Li, Zhang, and He 2012; Jia, Mi, and Zhang 2013). The traditional grey clustering analysis is generally based on the real number domain, which is not applicable when the sample value is an interval. Considering this problem, the researchers proposed interval grey clustering analysis (IGCA) (Zhou et al. 2013; Wang et al. 2015; Qian, Liu, and Xie 2016; Dang et al. 2017). However, the reported applications of this method in the construction industry are limited.

In summary, there is not enough emphasis on BIM application capability evaluation for enterprises in China. Only a few studies have focused on the issue. Moreover, previous studies have not found an appropriate method for BIM application capability evaluation. Therefore, based on five foreign maturity models and relevant domestic literatures, this paper
firstly established an evaluation index system for BIM application capability, and then constructed an IGCA-based assessment model for BIM application capability evaluation. Lastly, the model validity and applicability were verified through case studies.

3. Methodology

Considering the methods for evaluation, there are many commonly employed methods such as fuzzy comprehensive evaluation (FCE), AHP, grey correlation analysis and TOPSIS (Li and Yu 2013; Wang et al. 2017; Yu 2017; Wu and Hu 2020). However, the results obtained through FCE and AHP tend to be subjective, and because of the difficulty in determining the reference sequence or the optimal vector, the grey correlation analysis and TOPSIS may not be applicable to this study. In addition, structural equation model (SEM), principal component analysis (PCA), factor analysis (FA) and BP neural network are also popular methods for evaluation (Gunduz, Birgonul, and Ozdemir 2017; Ma, Shang, and Jiao 2018; Li 2019; Liu, Zhan, and Tian 2019). However, these methods require large data samples to conduct evaluation, which are not applicable to research due to the difficulty to obtain multiple samples. As discussed previously, grey clustering analysis has the advantages of both grey system theory and clustering analysis, and can solve the multi-index evaluation problem with small samples and poor information. The evaluation results by this method are intuitive and reliable. According to grey clustering analysis, the white-nization values of the clustering object for different clustering indices are summarized according to a number of grey numbers to determine the grey categories (Fu and Zou 2018). Moreover, for the issue of capability evaluation, it is difficult to accurately quantify the relevant indices and classify the grey categories of the evaluation objects due to the complexity of the reality and the incomplete information. In most cases, data range may be given as intervals based on existing information. On this account, interval grey clustering analysis (IGCA) was chosen for evaluation.

3.1. Related theory of interval grey number

The interval grey number refers to the uncertain value in a certain interval or a general number set (Zhou et al. 2013). In this paper, the entropy weight method and grey clustering analysis with interval grey number were applied to develop an evaluation model of BIM application capability. For this purpose, the basic concepts and algorithms of interval grey number are introduced, and interval grey number ordering is also discussed.

3.1.1. Basic concepts and algorithms

Assume $\otimes \in [\otimes^-, \otimes^+]$ is the interval grey number defined on the domain of discourse $\Omega$, and when $\Omega \in [0, 1]$, the interval grey number $\otimes$ is called the standard grey number. $\mu(\otimes) = \otimes^+ - \otimes^-$ is the measurement of the range of $\otimes$. In the absence of the value distribution information of interval grey number $\otimes$, we note $\otimes$ as the kernel of $\otimes$, where $\otimes = (\otimes^- + \otimes^+)/2$, and $g_0(\otimes)$ as the degree of greyness of $\otimes$, where $g_0(\otimes) = \mu(\otimes)/\mu(\Omega)$ (Guo et al. 2019; Liu, Fang, and Forrest 2010). For example, considering $\otimes = [2, 8]$ is the interval grey number defined on the domain of discourse $[0, 10]$, then the $\mu(\otimes) = 8 - 2 = 6$, $\mu(\Omega) = 10 - 0 = 10$, the $\otimes = (2 + 8)/2 = 5$, and the $g_0(\otimes) = 6/10 = 0.6$.

Considering the interval grey number $\otimes \in [\otimes^-, \otimes^+]$, it can alternatively be represented as $\hat{\otimes}(g_{11})$ or $\hat{\otimes}(r)$ ($\otimes(r) = \otimes^- + (\otimes^+ - \otimes^-)r, 0 \leq r \leq 1$), where $\hat{\otimes}(g_{11})$ is the simplified form and $\otimes(r)$ is the standardized form of interval grey number $\otimes$ (Wang et al. 2015; Qian, Liu, and Xie 2016). The two forms contain both the upper limit and lower limit information, and have the one-to-one correspondence with interval grey number, i.e. the two forms contain the same amount of information as the original interval grey number. Given an interval grey number $\otimes \in [\otimes^-, \otimes^+]$, we can represent it in simplified form or standardized form. On the contrary, when the simplified form or standardized form is known, we can also get the original interval grey number via the previous definition. For example, considering the example above, the simplified form of interval grey number $\otimes = [2, 8]$ is $\otimes = 5 \otimes 0$, and the standardized form is $\otimes (r) = 2 + (8 - 2) \times r = 2 + 6r, 0 \leq r \leq 1$.

The algorithm of interval grey numbers is the theoretical basis of grey system theory, which plays an important role in the application of interval grey numbers. The researches (Guo et al. 2019; Liu, Fang, and Forrest 2010; Li, Yin, and Yang 2017) have proposed the algorithm of interval grey numbers based on kernel and degree of greyness, which could avoid the problems caused by the original algorithm, such as the abnormal amplification of the degree of greyness. Assume there are two interval grey numbers $\hat{\otimes}_1 \in [\hat{\otimes}_1^-, \hat{\otimes}_1^+]$ and $\hat{\otimes}_2 \in [\hat{\otimes}_2^-, \hat{\otimes}_2^+]$, which are simply recorded as $\hat{\otimes}_1(\hat{\otimes}_{11})$ and $\hat{\otimes}_2(\hat{\otimes}_{21})$, then the algorithms of interval grey numbers are:

$$\hat{\otimes}_1(\hat{\otimes}_{11}) + \hat{\otimes}_2(\hat{\otimes}_{21}) = (\hat{\otimes}_1 + \hat{\otimes}_2)(\hat{\otimes}_{11} + \hat{\otimes}_{21})$$  \hspace{1cm} (1)

$$\hat{\otimes}_1(\hat{\otimes}_{11}) - \hat{\otimes}_2(\hat{\otimes}_{21}) = (\hat{\otimes}_1 - \hat{\otimes}_2)(\hat{\otimes}_{11} - \hat{\otimes}_{21})$$  \hspace{1cm} (2)

$$\hat{\otimes}_1(\hat{\otimes}_{11}) \times \hat{\otimes}_2(\hat{\otimes}_{21}) = (\hat{\otimes}_1 \times \hat{\otimes}_2)(\hat{\otimes}_{11} \times \hat{\otimes}_{21})$$  \hspace{1cm} (3)

$$\hat{\otimes}_1(\hat{\otimes}_{11})/\hat{\otimes}_2(\hat{\otimes}_{21}) = (\hat{\otimes}_1/\hat{\otimes}_2)(\hat{\otimes}_{11}/\hat{\otimes}_{21})$$  \hspace{1cm} (4)

$$k \cdot \hat{\otimes}_1(\hat{\otimes}_{11}) = (k \cdot \hat{\otimes}_1)(\hat{\otimes}_{11})$$  \hspace{1cm} (Suppose k is a real number)(5)
3.1.2. Interval grey number ordering

According to the ordering method based on precision and relative kernel (Liu, Fang, and Forrest 2010; Ma et al. 2017), the method for ranking interval grey numbers is as follows.

Suppose $\odot \in [0^-, 0^+]$ is the standard grey number. $\odot$ is the kernel of $\odot$, and $g^0(\odot)$ is the degree of greyness of $\odot$, then we note $\gamma(\odot)$ as the precision of $\odot$, where $\gamma(\odot) = 1/(1 + g^0(\odot))$, and $\delta(\odot)$ as the relative kernel of $\odot$, where $\delta(\odot) = \gamma(\odot) \times \odot$.

Considering the two standard grey numbers $\odot_1$ and $\odot_2$, then

1. $\delta(\odot_1) > \delta(\odot_2)$, then $\odot_1 > \odot_2$;
2. $\delta(\odot_1) < \delta(\odot_2)$, then $\odot_1 < \odot_2$;
3. $\delta(\odot_1) = \delta(\odot_2)$, then $\odot_1 = \odot_2$.

For example, considering the interval grey number $\odot_1 = [0.3, 0.6]$ and $\odot_2 = [0.4, 0.9]$, which are represented as $\odot_1 = 0.45(0.3)$ and $\odot_2 = 0.65(0.5)$. Then the $\gamma(\odot_1) = 1/(1 + 0.3) = 0.7692$, $\gamma(\odot_2) = 1/(1 + 0.5) = 0.6667$; $\delta(\odot_1) = 0.7692 \times 0.45 = 0.3461, \delta(\odot_2) = 0.6667 \times 0.65 = 0.4334$. $\delta(\odot_1) < \delta(\odot_2)$, so $\odot_1 < \odot_2$.

When the degree of greyness is equal to zero, the interval grey number becomes a real number, then the comparison of the interval grey numbers is converted into the comparison between real numbers.

3.2. Entropy weight method with interval grey number

In multi-attribute decision-making, different weights need to be assigned to each attribute due to its different influence on the evaluation object. The methods for determining the weights include Delphi method, analytic hierarchy process, sequential scoring method, etc. However, the weights obtained through these methods are subjective and arbitrary. The entropy weight method was chosen because it is an objective weighting method which determines the index weight according to the variability of indices (Ma et al. 2017).

Generally, the smaller the information entropy of an index is, the greater the variability of the index becomes, thus the more information it provides, and the greater its weight (Suchith Reddy, Rathish Kumar, and Anand Raj 2019; Dos Santos, Godoy, and Campos 2019). Entropy weight method could ensure the objectivity and accuracy of the index weights, so as to ensure the authenticity and reliability of the evaluation results. In this paper, the interval grey number is introduced into the entropy weight method to determine the weight of indices. The specific steps are as follows (Qian, Liu, and Xie 2016).

Step 1: Determination of the decision matrix

The evaluation value of the $i$-th expert on the $j$-th index is recorded as the interval grey number $\odot_{ij} \in [a_{ij}, b_{ij}] (i = 1, 2, \ldots; m; j = 1, 2, \ldots, n)$, which can also be written as $t_{ij} = a_{ij} + (b_{ij} - a_{ij}) \times r_{ij} (r_{ij} \in [0, 1])$ according to the definition of the standard interval grey number, so the decision matrix can be expressed as $T = (t_{ij})_{m \times n}$.

Step 2: Data standardization

In order to eliminate the influence of different dimensions between the indicators, the original data matrix should be normalized to $P = (p_{ij})_{m \times n}$. The standardization formula is as follows.

$$\tilde{p}_{ij} = \frac{t_{ij}}{\sum_{j=1}^{n} t_{ij}}$$

Step 3: Calculation of the information entropy

$$\hat{E}_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \tilde{p}_{ij} \ln \tilde{p}_{ij}$$

where $\hat{E}_j \in [E_j^-, E_j^+]$. The smaller the information entropy of evaluation index is, the more effective information it provides, and the greater the weight of the index will be.

Step 4: Calculation of the index weights

$$\hat{W}_j = \frac{1 - \hat{E}_j}{n - \sum_{j=1}^{n} \hat{E}_j}$$

where $\hat{W}_j \in [w_j^-, w_j^+]$.

$$w_j^- = \frac{1 - E_j^-}{n - \sum_{j=1}^{n} E_j^-}$$

$$w_j^+ = \frac{1 - E_j^+}{n - \sum_{j=1}^{n} E_j^+}$$

After obtaining the grey entropy weight of index $j$, $w_j = \frac{w_j^- + w_j^+}{2}$ is taken as the weight of index $j$ according to the theory of interval grey number “kernel”, which is normalized to get the final weight vector $w = (w_1, w_2, \ldots, w_n)$.

3.3. Evaluation method based on IGCA

The specific steps of the assessment are as follows.

Step 1: Construction of the interval grey number whitenization weight functions

The grey categories are classified according to the requirements of the project, and then the corresponding interval grey number whitenization weight functions of each grey category are determined. The whitenization weight function of index $j$ on the $k$-th grey category is denoted as $f^k_j(y) (y = 1, 2, \cdots, n; k = 1, 2, \cdots, s)$. $f^k_j [-, -] \equiv \gamma^k_j(3), \gamma^k_j(4), f^k_j \equiv \gamma^k_j(1), \gamma^k_j(2), -, -]$ are the lower
limit measure whitenization weight function, the moderate measure whitenization weight function and the upper limit measure whitenization weight function, respectively. \( \varphi_j^h(1) \), \( \varphi_j^h(2) \), \( \varphi_j^h(3) \) and \( \varphi_j^h(4) \) are, respectively, the first, second, third and fourth turning points of the whitenization weight function, where \( \varphi_j^h(i) \in \left[ \varphi_j^h(i)^-, \varphi_j^h(i)^+ \right] \) \( i = 1, 2, 3, 4 \). The three interval grey number whitenization weight func-

\[
 f_j^h(\varrho_j) = \begin{cases} 
 0 & \varrho_j^2 < 0 \text{ or } \varrho_j^2 \geq \varphi_j^h(4)^+ \\
 1(\varrho_j^2) & \varrho_j^2 \in [0, \varphi_j^h(3)] \text{ and } \varrho_j^2 < 0 \\
 1 & 0 \leq \varrho_j^2 \leq \varphi_j^h(3)^- \\
 \frac{\varrho_j^2(\varrho_j^2-\varphi_j^h(1))}{(\varrho_j^2-\varphi_j^h(2))(\varrho_j^2-\varphi_j^h(3))(\varrho_j^2-\varphi_j^h(4))} & \varrho_j \in [\varrho_j^h(3), \varrho_j^h(4)] \\
 0 & \varrho_j^2 > \varphi_j^h(4) \text{ and } \varrho_j^2 < \varphi_j^h(4)^+ 
\end{cases}
\]

The three interval grey number whitenization weight func-

\[
 f_j^h(\varrho_j) = \begin{cases} 
 0 & \varrho_j^2 < 0 \text{ or } \varrho_j^2 \geq \varphi_j^h(4)^+ \\
 1(\varrho_j^2) & \varrho_j^2 \in [0, \varphi_j^h(3)] \text{ and } \varrho_j^2 < 0 \\
 1 & 0 \leq \varrho_j^2 \leq \varphi_j^h(3)^- \\
 \frac{\varrho_j^2(\varrho_j^2-\varphi_j^h(1))}{(\varrho_j^2-\varphi_j^h(2))(\varrho_j^2-\varphi_j^h(3))(\varrho_j^2-\varphi_j^h(4))} & \varrho_j \in [\varrho_j^h(3), \varrho_j^h(4)] \\
 0 & \varrho_j^2 > \varphi_j^h(4) \text{ and } \varrho_j^2 < \varphi_j^h(4)^+ 
\end{cases}
\]

The three interval grey number whitenization weight func-

\[
 f_j^h(\varrho_j) = \begin{cases} 
 0 & \varrho_j^2 < 0 \text{ or } \varrho_j^2 \geq \varphi_j^h(4)^+ \\
 1(\varrho_j^2) & \varrho_j^2 \in [0, \varphi_j^h(3)] \text{ and } \varrho_j^2 < 0 \\
 1 & 0 \leq \varrho_j^2 \leq \varphi_j^h(3)^- \\
 \frac{\varrho_j^2(\varrho_j^2-\varphi_j^h(1))}{(\varrho_j^2-\varphi_j^h(2))(\varrho_j^2-\varphi_j^h(3))(\varrho_j^2-\varphi_j^h(4))} & \varrho_j \in [\varrho_j^h(3), \varrho_j^h(4)] \\
 1 & \varrho_j^2 > \varphi_j^h(4) \text{ and } \varrho_j^2 < \varphi_j^h(4)^+ 
\end{cases}
\]

The three interval grey number whitenization weight func-

\[
 f_j^h(\varrho_j) = \begin{cases} 
 0 & \varrho_j^2 < 0 \text{ or } \varrho_j^2 \geq \varphi_j^h(4)^+ \\
 1(\varrho_j^2) & \varrho_j^2 \in [0, \varphi_j^h(3)] \text{ and } \varrho_j^2 < 0 \\
 1 & 0 \leq \varrho_j^2 \leq \varphi_j^h(3)^- \\
 \frac{\varrho_j^2(\varrho_j^2-\varphi_j^h(1))}{(\varrho_j^2-\varphi_j^h(2))(\varrho_j^2-\varphi_j^h(3))(\varrho_j^2-\varphi_j^h(4))} & \varrho_j \in [\varrho_j^h(3), \varrho_j^h(4)] \\
 1 & \varrho_j^2 > \varphi_j^h(4) \text{ and } \varrho_j^2 < \varphi_j^h(4)^+ 
\end{cases}
\]

The three interval grey number whitenization weight func-

The whitenization weight values are calculated according to the whitenization weight function determined in step 1. The turning points and index values are

Step 2: Calculation of whitenization weight values

The whitenization weight values are calculated according to the whitenization weight function determined in step 1. The turning points and index values are

Step 3: Determination of grey clustering weight

The weight reflects the importance degree of different indexes to the evaluated objects. The entropy weight method based on interval grey number was applied to determine the index weight.
Figure 1. Lower limit measure whitenization weight function.

Figure 2. Moderate measure whitenization weight function.

Figure 3. Upper limit measure whitenization weight function.

According to the principle of maximum membership, the grey category of the evaluation object can be determined by the following formula.

$$\sigma_k = \max_{1 \leq k \leq 3} \{\sigma^k\} = \sigma^{k^*}$$  \hspace{1cm} (15)

Thus the grey category of the evaluation object is $k^*$.

4. Proposed model of BIM application capability evaluation

The proposed evaluation model was an approach for assessing the BIM application capabilities of enterprises. Assessments using the approach enable the organizers to understand current levels of BIM application capabilities. The assessment results could provide baseline for improvements in BIM usages. The evaluation model possessed a schema in which evaluation index system, application capability levels, and evaluation process were defined to facilitate BIM application capability assessments.

4.1. Construction of evaluation index system

Considering that related Chinese standards and engineering project management models are different from those of foreign countries, the five internationally recognized BIM maturity models, namely NBIMS CMM, BIM Proficiency Matrix, BIM Maturity Matrix, BIM Quick Scan and VDC Scorecard, may not be completely suitable for domestic situations. Therefore, based on the five maturity models, this study combined the relevant domestic literature and Chinese BIM-related standards to develop the evaluation index system. The evaluation index system was confirmed by experts who have rich experience in BIM application and project management. The sources of each index are shown in Table 1, and the evaluation index system is shown in Table 2.

4.2. Division of BIM application capability levels

It was necessary to decide how many application capability levels should be defined to cover the different levels of BIM utilization. Various multi-stage divisions of BIM maturity have been proposed in the literature. For example, six levels of BIM maturity for NBIMS CMM and BIM QuickScan; five levels of BIM maturity for BIM PM and BIM MM; four levels of BIM maturity for VDC Scorecard and Multi-functional BIM MM have been defined. However, it has been observed that four-stage divisions have been proposed and tested more frequently (King and Teo 1997). In addition, according to Yilmaz, Akcamete, and Demirors (2019), four levels of BIM capability appear to be sufficient without omitting any significant type of BIM utilization. Therefore, we created four levels of BIM application capability starting from Level 0 to Level 3. To define the BIM
Table 1. Sources of evaluation indices for BIM application capabilities.

| Indices          | Source of indices                                      |
|------------------|-------------------------------------------------------|
|                  | NBIM CMM | BIM MM | BIM PM | VDC Scorecard | BIM Quick Scan | Wang, Wang, and Peng (2017) | Yu (2017) | Wang and Li (2018) |
| Technical        | C1       | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         | ✓                |
|                  | C2       | ✓      | ✓      | ✓            | ✓             |                         |           |                  |
|                  | C3       | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C4       | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C5       | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C6       | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
| Organization and management | C10      | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C11      | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C12      | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C13      | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |
|                  | C14      | ✓      | ✓      | ✓            | ✓             | ✓                       | ✓         |                  |

Note: “*” - (Shanghai Housing and Urban-Rural Construction Management Committee 2017).

Table 2. Index system for BIM application capability evaluation.

| Indices                   | Indices interpretation and explanation                                      |
|---------------------------|-------------------------------------------------------------------------------|
| Technical                 | Richness and Accuracy of BIM-Related Data and Information (C1)               |
|                           | Rich and accurate data on both graphical and non-graphical information and    |
|                           | life cycle information uses                                                   |
|                           | Model-Based Calculations and Analysis (C2)                                   |
|                           | Model-based optimization, simulation, cost accounting, schedule control and   |
|                           | other calculations and analysis                                               |
|                           | BIM-Related Software and Hardware Configuration (C3)                         |
|                           | BIM software selections and hardware configurations for BIM uses              |
|                           | Interoperability and coordination of BIM-related data (C4)                   |
|                           | Interoperability and coordination of BIM data among multiple disciplines/      |
|                           | stakeholders                                                                  |
|                           | Secondary Development Capability of BIM Software (C5)                        |
|                           | Secondary development capability in BIM software uses                        |
| Organization and          | BIM Strategies and Goals (C6)                                                |
| management                | BIM vision, strategic planning and goals for BIM usages                      |
|                           | Attitude of Management and Leadership towards BIM (C7)                      |
|                           | Management and Leadership’s accurate cognition and continuous support        |
|                           | towards BIM                                                                   |
|                           | Perfectness of BIM-Related Standards (C8)                                    |
|                           | Perfectness of BIM-Related Standards at organizational and project level      |
|                           | Completeness of BIM Business Processes (C9)                                  |
|                           | Completeness of processes (such as operation, change, and delivery, etc.) at  |
|                           | the BIM usages level                                                          |
| Human Aspect              | Applicability of Organizational Structure (C10)                             |
|                           | Organizational structure is adaptable to BIM usages                         |
|                           | Experiences, Skills and Knowledge of BIM Staff/Stakeholders (C11)           |
|                           | BIM-Related Staff Experiences, Skills and Knowledge of BIM Staff/Stakeholders|
|                           | BIM-Related Training and Education (C12)                                     |
|                           | BIM-Related Training and Education for Staff/Stakeholders                    |
|                           | BIM-Related Responsibilities and Roles (C13)                                 |
|                           | Arrangement of BIM-Related Responsibilities and Roles                        |

capability levels, Multi-functional BIM MM (Liang et al. 2016) and BIM-CAREM (Yilmaz, Akcamete, and Demirors 2019) were followed, and the actual situation of BIM application in Chinese enterprises was also considered. BIM application capability levels are presented below. The level descriptions of indices are shown in Table 3.

- BIM application capability level 0-Incomplete BIM: BIM is not implemented or partially implemented but there are no changes and resource commitments to support BIM.
- BIM application capability level 1-Performed BIM: BIM is implemented to achieve the business process purpose and is used to perform base practices and produce standalone BIM outcomes. However, BIM has not been integrated into the business processes, and there is no significant BIM-based collaboration and data exchange between stakeholders and business processes.
- BIM application capability level 2-Integrated BIM: The previously performed BIM is implemented using an integrated BIM supporting collaboration and data exchange between stakeholders and business processes.
- BIM application capability level 3-Optimized BIM: The previously integrated BIM is used at organizational level and is continuously improved to achieve the strategies and goals of the organization.

4.3. Evaluation process

The proposed approach to evaluate BIM application capabilities can be presented in three phases.

Phase I—In the first phase, a team of experts give their judgment on assessment indices score according to the BIM implementation. In this phase, the proposed index system will be explained to the experts.

Phase II—In the second phase, the decision matrix is constructed based on the scores given by experts. The
interval-entropy weight method utilizes this matrix to estimate weights of the indices. The outputs of this phase will be the input (weights of the indices and decision matrix) of phase III.

Phase III—At last, in the third phase, the IGCA method (as described earlier) is used to evaluate the organization and determine the BIM application capability level of the organization.

5. Application of proposed approach

5.1. Case study

This paper took company A in China as an example. Company A is a construction enterprise founded in the 1940s with many years of experience in construction engineering, municipal engineering, fire engineering and architectural design. It is the pioneer of BIM application in China and has been using BIM for about 10 years. At present, Company A has implemented BIM in the whole life cycle of the project and has preliminarily established a BIM data platform including project data such as schedule, contract, cost, quality, drawings, etc., and has also realized the integration of BIM with standardization, informatization and cloud technology. We conducted our case study in company A based on the proposed evaluation model.

Step 1: Development of the decision matrix

Three experts were invited to deliver their judgments on index values based on the BIM implementation of company A, which were denoted in the interval grey numbers in the domain of [0,100]. These experts were selected on the basis of their rich experience in construction project management, and all of them have many years of BIM experience. The decision matrix was constructed.
based on the index values given by experts, which was as follows:

\[
\mathbf{A}( \otimes_y ) = \begin{bmatrix}
(58, 60) & (73, 75) & (81, 84) & (58, 62) \\
(64, 67) & (63, 66) & (75, 77) & (56, 60) \\
(56, 59) & (70, 72) & (79, 82) & (64, 67) \\
(78, 80) & (71, 73) & (80, 82) & (74, 78) \\
(69, 72) & (64, 67) & (78, 81) & (84, 86) \\
(74, 76) & (68, 70) & (84, 86) & (87, 90) \\
(75, 77) & (56, 58) & (75, 79) & (67, 70) \\
(71, 74) & (60, 64) & (82, 85) & (72, 74) \\
(79, 82) & (58, 60) & (77, 80) & (76, 79)
\end{bmatrix}
\]

Step 2: Determine the index weights

According to the interval-entropy weight method introduced in Section 3.2, the index weights were calculated as follows.

Considering the first indicator \(j = 1\), the interval grey numbers were written in standardized form with \(t_{11} = 58 + 2r_{11}, t_{21} = 64 + 3r_{21}, t_{31} = 56 + 3r_{31}\). Then

\[
\bar{p}_{11} = \frac{58 + 2r_{11}}{178 + 2r_{11} + 3r_{21} + 3r_{31}}
\]

\[
\bar{p}_{21} = \frac{64 + 3r_{21}}{178 + 2r_{11} + 3r_{21} + 3r_{31}}
\]

\[
\bar{p}_{31} = \frac{56 + 3r_{31}}{178 + 2r_{11} + 3r_{21} + 3r_{31}}
\]

\[
\bar{E}_1 = -\frac{1}{ln3} (\bar{p}_{11} ln\bar{p}_{11} + \bar{p}_{21} ln\bar{p}_{21} + \bar{p}_{31} ln\bar{p}_{31})
\]

Then we obtained \( \bar{E}_1 \in [0.9972, 0.9994] \) through MATLAB software. Similarly, the entropy values of all indices can be obtained. Then, according to the equations in step 4 of Section 3.2, the index weights were obtained as shown in Table 4.

Step 3: Determine the BIM application capability level

According to the division of BIM application capability levels in the previous section, the grey category was divided into four. In this phase, we first determined the whitenization weight functions of indices according to the expert opinions, which were as follows.

\[
f^1 = [−, −, (52, 54), (62, 65)],
\]

\[
f^2 = [(52, 54), (62, 65), −, (78, 82)],
\]

\[
f^3 = [(62, 65), (78, 82), −, (90, 95)],
\]

\[
f^4 = [(78, 82), (90, 95), −, −].
\]

Then we took the average of the index values given by the three experts in step 1 as the index scores, which were written in simplified form and denoted as \( \otimes_y \). Then we calculated the whitenization weight values of indices according to Equations (11 – 13).

Finally, based on the index weights obtained in step 2, we calculated the comprehensive clustering coefficients according to Equation (14). Whitenization weight values and comprehensive clustering coefficients are shown in Table 5.

5.2. Results and discussion

According to Equation (15) and the ordering method introduced in Section 3.1.2, the BIM application capability of the enterprise was found at level 2-Integrate BIM, which is consistent with the Chinese construction industry’s qualitative assessment on BIM application capability of company A. In addition, we fed the results back to the BIM managers and BIM engineers of the enterprise to discuss with them, all of the interviewees stated that the evaluation results were the same as their expected BIM application capability level. The judgment of the construction industry and the feedback from company A verified the effectiveness of the proposed evaluation model.

According to the index weights in Table 4, the key indices that affect the BIM application capability are \( C_1 \)-Richness and Accuracy of BIM Related Data and Information, \( C_2 \)-Model Based Calculations and Analysis, \( C_3 \)-Interoperability and coordination of BIM related data, \( C_{13} \)-BIM Related Responsibilities and Roles, and \( C_9 \)-Completeness of BIM Business Processes. For Company A, the improvement of these indices could facilitate the improvement of BIM application capability. In addition, based on the evaluation results in Table 5, Company A could identify the performance of their BIM utilizations, and at the same time could determine the current level of each index in conjunction with the level description in Table 3, thus could enable continuous BIM improvements.

The IGCA-based assessment approach could determine the BIM application capability of the enterprise, which could also identify the key factors affecting BIM performance. It indicates that this approach provides a new idea for BIM application capability evaluation.
and realizes the conversion between qualitative concepts and quantitative values of capability evaluation, and also allows the index values to be given in the form of interval grey number, thus could facilitate scientific and reliable evaluation results.

6. Conclusion

Assessment of enterprise BIM application capability is crucial to the improvement of BIM performance and the development of BIM technology. This paper introduced interval grey clustering analysis to construct an evaluation model for BIM application capability. The model considers the problem that the index values are difficult to be accurately quantified under the incomplete and uncertain information, and employs the interval grey number to deal with the BIM application capability evaluation by defining the levels of capability in terms of intervals and taking the index values as interval data, which could make the evaluation more in line with the reality and the evaluation results more scientific and reliable.

The proposed evaluation model consists of three elements: the evaluation index system, the BIM application capability levels and the evaluation process. The index system includes three dimensions of technical, organization and management, and human aspect, which are constructed based on relevant literature analysis and expert opinions. Four capability levels are defined to map the evolution of each metric. In order to determine the index weights, the interval-entropy weight method was performed to assign the interval weight for each indicator. The IGCA method was then applied to evaluate BIM application capability. Finally, a case study was performed to verify the validity of the evaluation model. Based on the feedback of the interviewees on the evaluation results, it indicates that the proposed evaluation model could be used to effectively identify the BIM capability levels of enterprises. The evaluation model could provide a new way to evaluate BIM usages and enable continuous BIM improvements.

One limitation in this research should be noted. The assessment of the indices reflects the cognition of the personnel; thus, the results can be affected by the characteristics of the respondents. In the future research, we plan to expand the number of respondents to assign weight for each respondent to enhance the reliability of the assessment and conduct other cases to further validate the model.

Acknowledgments

The authors would like to acknowledge the National Natural Science Foundations of China and Key R&D and promotion Special Projects of Henan Province, China for financially supporting this work, and express our appreciation to the experts for providing useful data, valuable information, and helpful comments during our research.

The authors would like to extend our sincere gratitude to our teacher, Danying Gao, for his instructive advice and useful suggestions on our thesis. We are deeply grateful of his help in the completion of this thesis.

Author contributions

Ailing Wang proposed innovation points, provided research platforms and research funds, guided and modified the manuscript. Mengqi Su did the data collection and analysis, and wrote the manuscript. Shaonan Sun guided and modified the manuscript. Yuqin Zhao provided the case information.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Natural Science Foundation of China under Grant [number 51709115]; National Natural Science Foundation of China under Grant [number 71801195]; and Key R&D and promotion Special
Projects of Henan Province under Grant [number 182102210066].

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