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A linguistic group decision-making framework for bid evaluation in mega public projects considering carbon dioxide emissions reduction

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Abstract

Green construction is to conserve the resources and reduce the negative impact of construction activities on the environment to the maximum extent, with scientific management and technological progress under the premise of ensuring the quality, safety and other basic requirements. Recent years, accompanied by the rapid development of construction industry, a considerable proportion of energy and resources, particularly high-carbon materials, is consumed in the construction activities, emitting mass greenhouse gases, which have a damaging impact on the environment. This is especially for the mega public projects. Therefore, under the green and sustainable perspective, actions to control carbon dioxide (CO2) emissions in the construction industry are imperative. In this case, if CO2 emissions reduction can be considered beforehand during the bid evaluation stage, contractors will be guided by bid evaluation indicators and therefore improve their construction schemes, enabling the construction phase to be green, energy saving and sustainable. This is because bid evaluation indicators can serve as guiding effect on the contractors. Given that CO2 emissions are rarely given sufficient consideration in traditional bid evaluation, this study conducts a systematic analysis to identify major sources of CO2 in construction phase and attempts to develop a conceptual computational model in terms of CO2 emission. Then, a linguistic group decision-making framework for bid evaluation in mega public projects considering CO2 emissions reduction is developed. In this framework, entropy, relative entropy, the standard deviation method and weighted aggregation operators are applied to determine the indicator weights, the expert weights and the information aggregation in bid evaluation decision-making. Finally, a scenario comparison between the proposed linguistic group decision-making bid evaluation framework and the traditional framework is made through a case study, and the scientific basis and reliability of this new framework are validated. The establishment of this framework can enrich the decision-making methods in construction

management field. And it can provide meaningful reference for owners to choose the most qualified contractors and spur contractors to improve their construction schemes, enabling construction phase to be green, energy saving and sustainable.

1. Introduction

The rapid development of the construction industry has been accompanied by the considerable consumption of high-carbon materials and large energy expenditures, resulting in mass CO_2 emissions and the construction industry being classified as a high energy-consumption industry in many countries (Li and Liu, 2010; Tsai et al., 2011, 2012; Dodoo et al., 2009; Abanda et al., 2013; Zhang et al., 2014; Liu et al., 2010; Huo et al., 2015; Lin and Liu, 2015; Wang et al., 2016; Hong et al., 2016). In China, for example, the construction of one square kilometer of concrete building can result in carbon emissions of approximately 0.8e1 ton, and the level of greenhouse gas emissions of the construction industry contributes to 25% of the level of the entire national economy (China Statistics Yearbook). In developed countries, 50% of total energy costs are closely related to or result from the construction industry (Gonzalez and Navarro, 2006; Liu, 2013; Cui et al., 2014; Liao et al., 2014; Yao et al., 2015). Therefore, reducing CO_2 emissions from the construction industry should become the highest priority for countries that are attempting to mitigate global climate change.

Currently, scholars pay attention to the Life Cycle Assessment of CO_2 emissions in the construction industry, but the corresponding treatment measures are actually rare. Research on CO_2 emissions reduction in the bid evaluation stage is also very scarce (Marland and Turhollow, 1991; Paustian et al., 2000; Lal, 2004; Lai et al., 2004; Adler et al., 2007; Blengini and Carlo, 2010; Tsai et al., 2012). The traditional bid evaluation indicators are mainly categorized into three aspects, i.e., technology, the tendered price and health/safety/environment (Palaneeswaran and Kumaraswamy, 2001; Lai et al., 2004; Watt et al., 2009, 2010; Liu et al., 2013, 2014, 2015a, 2017). Bid evaluation is not only an important step in the bid process but also central to the entire bid activity (Yan, 2011; Liu et al., 2014). The bid evaluation indicators can have a guided effect on construction enterprises, and bidders will therefore tailor and improve their construction plans according to specific evaluation indicators to win the bid. This is especially true for mega public projects, which are mainly constructed with publicly financed funds from the central or local government or through government contract financing. The government's aim, which is to raise quality of life, maximize social benefits and minimize environmental pollution during the construction phase, is suggested to be one of the most important criteria by which the success of a project is judged. Thus, considering CO_2 emissions reduction in the bid evaluation of mega public projects can serve as a guide that can motivate contractors to improve their construction techniques, use green construction and minimize deleterious environmental effects.

In fact, the uncertainty inherent to construction projects makes it difficult for experts to accurately judge various aspects of the tender submission; thus, the bid evaluation of construction projects is a complex multi-attribute group decision-making problem (Liu et al., 2013, 2014, 2015a, 2017). The linguistic approach is an approximate technique for addressing this issue that incorporates the qualitative features of the tender submission in terms of linguistic values using linguistic variables (Hatush and Skitmore, 1997; Alsugair, 1999; Ng and Skitmore, 2001; Watt et al., 2009, 2010; Xu and Wang, 2011; Xu et al., 2012; Xu et al., 2013, 2016; Liu et al., 2015a, 2017). Linguistic information is widely used in practice because it is more suitable to the features of human decision-making and corresponds to real-world situations (Chan and Chan, 2004; Liu et al., 2014; Xu et al., 2014, 2015a, 2015b; 2015c; Zhang et al., 2016). For these reasons, in this study, the linguistic group decision-making model is applied to bid evaluation. However, considering the extreme difficulty of measuring CO_2 emissions at the bid evaluation stage, this study establishes a group expert decision-making framework for bid evaluation of major public projects considering CO_2 emissions reduction. Entropy and relative entropy are used to determine the indicator weights, the standard deviation method is used to determine the expert weights, and the information aggregation model is used to aggregate the evaluation information. A further study will be conducted to compute the amount of CO_2 emissions with the aid of a computer.

The remainder of this paper is organized into six sections. Following the Introduction, Section 2 presents the traditional bid evaluation indicators and carbon source analysis during the construction phase and the new bid evaluation indicator system considering CO_2 emissions. Section 3 performs a systematic analysis of the CO_2 sources and presents the conceptual computational model for CO_2 emissions based on the Intergovernmental Panel on Climate Change (IPCC) computational method. Then, the underlying framework of the model is presented. Section 4 establishes the bid evaluation decision-making framework for mega public projects considering CO_2 emissions reduction. Section 5 evaluates the framework considering and not considering CO_2 emissions reduction with a case study to verify the efficacy and scientific basis of considering CO_2 emissions reduction in the model. Section 6 presents the shortcomings of this work and future prospects.

2. Literature review

To date, many scholars have conducted research on the project bid evaluation indicators and carbon sources in construction projects. This section consists of a literature review of the traditional project bid evaluation indicator system and the carbon sources in construction projects. The results of the comprehensive literature review are used to develop a new bid evaluation indicator system for mega public projects considering CO_2 emissions.

2.1. Traditional bid evaluation indicators

In light of the literature review, making a decision among alternatives in the bid evaluation stage is typically based on a number of indicators. The bid evaluation indicators play a significant role in the bid evaluation because they have a guiding effect on contractors, encouraging them to improve their construction technology to meet the bid requirement. Previous researchers have conducted many studies on contractor selection and considered a variety of indicators. The indicators that they considered can generally be grouped into three main categories, and each category can be further divided into specific sub-indicators. These categories are presented below, and the specific indicators are shown in Table 1.

(1) Technology (Hatush and Skitmore, 1997; Alsugair, 1999; Ng and Skitmore, 2001; Watt et al., 2009, 2010; Sarkis et al., 2012; Mahdi et al., 2013; Sun et al., 2015; Liu et al., 2015a; Nasab and Ghamsarian, 2015; Khan and Hosany, 2016; Liu et al., 2017). Technology has been evaluated by various scholars and is considered to be the most critical indicator of a company's technical capacity A contractor must demonstrate the technical capacity to perform the activities that are required for the specific project to compete for the mega public project. This mainly entails the contractors' construction organization design, key engineering technical solution, and quality control ability.

(2) Tendered price (Alsugair, 1999; Lai et al., 2004; Watt et al., 2009, 2010; Mahdi et al., 2013; Sun et al., 2015; Liu et al., 2013, 2015a, 2017; Khan and Hosany, 2016; Xie, 2016). This price, which is the price that a contractor quotes to accomplish the project objectives, is also a crucial indicator that has been studied by various scholars. The contractor who bids the lowest will be

preferred by the client. The tendered price discloses the resources that are possessed by the general contractor, which also demonstrates the competitiveness of the contractor to the client (Alsugair, 1999; Ng and Skitmore, 2001; Lai et al., 2004; Watt et al., 2009, 2010; Sarkis et al., 2012; Liu et al., 2017, 2013, 2015a,b).

(3) Health/Safety/Environment (HSE) (Hatush and Skitmore, 1997; Ng and Skitmore, 2001; Palaneeswaran and Kumaraswamy, 2001; Sarkis et al., 2012; Liu et al., 2014, 2015a, 2017; Nasab and Ghamsarian, 2015). HSE is also a significant indicator of the capability of a contractor to be socially responsible toward the company's employees and the public at large. This indicator encourages contractors to establish and maintain effective systems for managing the risk presented by the project to ensure the health and safety of their employees. Construction-related environmental issues draw more attention from governments, nongovernmental organizations and the general public (Harris and Holt, 1999). HSE is highly prioritized in many reputable enterprises, and contractors who would like to deliver a project smoothly must have a good capability for addressing this issue.

Table 1
Bid evaluation indicators.

#	Category	Specific indicators
1	Technology	Construction organization design (Lai et al., 2004; Liu et al., 2015a; Nasab and Ghamsarian, 2015; Khan and Hosany, 2016), Technical solution of key engineering (Hatush and Skitmore, 1997; Alsugair, 1999; Ng and Skitmore, 2001; Watt et al., 2009; Watt et al., 2010; Khan and Hosany, 2016; Xie, 2016; Liu et al., 2017), quality control (Palaneeswaran and Kumaraswamy, 2001; Chan and Chan, 2004; Sarkis et al., 2012; Mahdi et al., 2013; Liu et al., 2014; Sun et al., 2015)
2	Tendered price	Bid price (Lai et al., 2004; Watt et al., 2009; Watt et al., 2010; Liu et al., 2014; Sun et al., 2015; Liu et al., 2015a; Nasab and Ghamsarian, 2015; Liu et al., 2016; Khan and Hosany, 2016; Xie, 2016; Liu et al., 2017), capital price (Watt et al., 2009; Sarkis et al., 2012; Mahdi et al., 2013; Liu et al., 2014), operating costs (Alsugair, 1999; Watt et al., 2009; Liu et al., 2015a; Nasab and Ghamsarian, 2015; Khan and Hosany, 2016; Xie, 2016)
3	Health/safety/ environment (HSE)	Corporate environmental policy (Watt et al., 2009; Liu et al., 2015a; Nasab and Ghamsarian, 2015; Khan and Hosany, 2016; Xie, 2016), safety plan (Hatush and Skitmore, 1997; Ng and Skitmore, 2001; Palaneeswaran and Kumaraswamy, 2001), safety performance (Palaneeswaran and Kumaraswamy, 2001; Mahdi et al., 2013; Sun et al., 2015; Liu et al., 2015a; Nasab and Ghamsarian, 2015)

An exhaustive presentation of the specific indicators of the above-mentioned categorizes is shown in Table 1.

Table 1 shows that carbon emissions indicators have not been considered in the traditional bid evaluation indicator system and only general indicators have been considered, which is not comprehensive. Owing to the externality of public projects, construction activities generate large amounts of CO_2 emissions, and it is suggested that CO_2 emissions reduction be considered in the bid evaluation process. Doing so will have a significant effect on the bidders because contractors will improve their construction plan and technique and make construction activities more sustainable to meet the bid requirement. This is beneficial to both owners and contractors as well as to other stakeholders of the public project, especially in our current period, in which people's environmental awareness is increasingly high. In the next sub-section, the carbon sources in the construction phase are specifically analyzed, and carbon emissions indicators are identified.

2.2. Analysis of carbon sources in the construction phase and the identification of carbon emissions indicators

CO_2 emissions originate from carbon sources. Analyzing the sources of CO_2 means seeking the activities that produce CO_2, namely, the carbon footprint, which is a key for computing the total carbon emissions. The main sources of CO_2 emissions in construction activities are associated with the construction design and use stage; however, research on the construction stage is in its infancy (Li et al., 2011; Lin and Liu, 2015; Wang et al., 2016; Hong et al., 2016). Humans generally concentrate on the highest levels of energy consumption and emissions during the building life cycle based on the building use stage; thus, the key to saving building energy is the energy consumption in the building use stage. This view ignores the critical issue that the percentage of the building construction stage in the entire life cycle is much smaller than the design and use stage. Currently, the building service life is generally 50 years according to the Chinese Construction Standard, whereas the building construction period is often only one year or even several months. In addition, there are a large number of new buildings that are built every year. Thus, the energy consumption and environmental pollution problems caused by building construction cannot be ignored. Previous scholars have conducted many studies on carbon sources, and many outcomes have been produced.

However, different researchers have different definitions of carbon emissions. Analyzing carbon emissions sources is fundamental to identifying the carbon emissions indicators that will be considered in the bid evaluation stage. Some representative carbon emissions definitions by scholars are presented below.

Li et al. (2011) defined the direct CO_2 emissions from construction activities as the direct discharges of greenhouse gas from power fuel combustion in machinery; indirect CO_2 emissions were defined as the CO_2 emissions from electric machinery and steam energy. Other CO_2 emissions from material consumption and construction waste are known as immeasurable CO_2 emissions. Li et al. (2011) also identified machinery and material use as the major contributors to CO_2 emissions. Energy consumption is what ultimately causes CO_2 emissions. Furthermore, CO_2 sources are classified as direct sources, i.e., fuel, and indirect sources, i.e., power and steam, depending on whether there is a direct or indirect relationship between the power energy and the CO_2 emissions.

Zhou (2011) reported that CO_2 sources from construction mainly consist of transportation CO_2 emissions, on-site CO_2 emissions, cast-off CO_2 emissions and carbon sinks in construction. The calculations of transportation CO_2 emissions should take the transportation method, the total amount of transportation, the distance traveled, the type of vehicles and vehicle efficiency into consideration. The calculations of on-site CO_2 emissions should emphasize the construction tools, the construction residence, office lighting and temporary housing. Cast-off CO_2 emissions mainly consist of CO_2 emissions from transportation and disposal; carbon sinks in construction are mainly associated with the increase in the total amount of carbon sinks by construction spot afforestation and CO_2 absorption.

Jiang et al. (2012) proposed that the overhead viaduct would directly or indirectly generate many greenhouse gases such as CO_2 during the entire life period; however, the most gas was generated in the construction period. Jiang et al. (2012) classified the sources of CO_2 emissions in overhead viaduct construction into two categories: the production of building materials and construction machinery. The

CO_2 sources from building materials are mainly related to energy consumption (from coal, diesel oil, etc.) during the construction phase, the disposal of raw materials (such as limestone in cement production) and the consumption of working substances in energy consumption (such as industrial water). The major sources of CO_2 in overhead viaduct construction are the prefabrication of segment beams, the transportation process and installation activities.

The aforementioned literature review shows that the materials used by bidding companies for permanent works share similar characteristics. Therefore, this study only considers the CO_2 emissions that result from different construction plans/schemes proposed by different contractors for the works specified in bidding documents. This study summarizes the outcomes of the abovementioned scholars and other previous scholars' research on carbon sources and groups the carbon sources into the following five categories: CO_2 emissions from machinery, CO_2 emissions from offsite transportation, CO_2 emissions from the deterioration of temporary projects, CO_2 emissions from construction assistance and management, and carbon sinks in construction. Each type of carbon source contains several specific related attributes that are the key components in calculating the amount of carbon emissions. For example, the key attributes/components for calculating CO_2 emissions from machinery are the use time of all types of construction equipment, the types of energy consumption of all types of construction equipment and the CO_2 conversion coefficient of all types of energy. Due to the space limitations of this paper, attributes related to other categories are not presented in this section but are all shown in Fig. 1. These carbon emissions indicators are the foundation for establishing the comprehensive bid evaluation indicator system in the following section.

2.3. Establishment of a bid evaluation indicator system for mega public projects considering CO_2 emissions reduction

From the traditional bid evaluation indicator system and the carbon emissions analysis noted above, we can observe that it is necessary to consider CO_2 emissions in the bid evaluation process of mega public projects, which will make the indicator system more comprehensive. The bid evaluation indicators have a guiding effect on contractors, stimulating them to improve their construction technology and scheme and to make their construction process green, less energy consuming and sustainable. Accordingly, a comprehensive bid evaluation indicator system for mega public project that incorporates CO_2 emissions reduction is established, as shown in Fig. 2. This indicator system is relatively comprehensive because it combines the traditional bid evaluation indicator system with the carbon emissions indicators in the course of the construction phase. Different major public projects vary in complexity, scale and other characteristics; therefore, the specific indicators for this indicator system should be adjusted (added or deleted) depending on the characteristics of the specific project.

3. Methodology

In this study, based on the traditional project bid evaluation

Fig. 1. Analysis of carbon dioxide sources in the construction process.

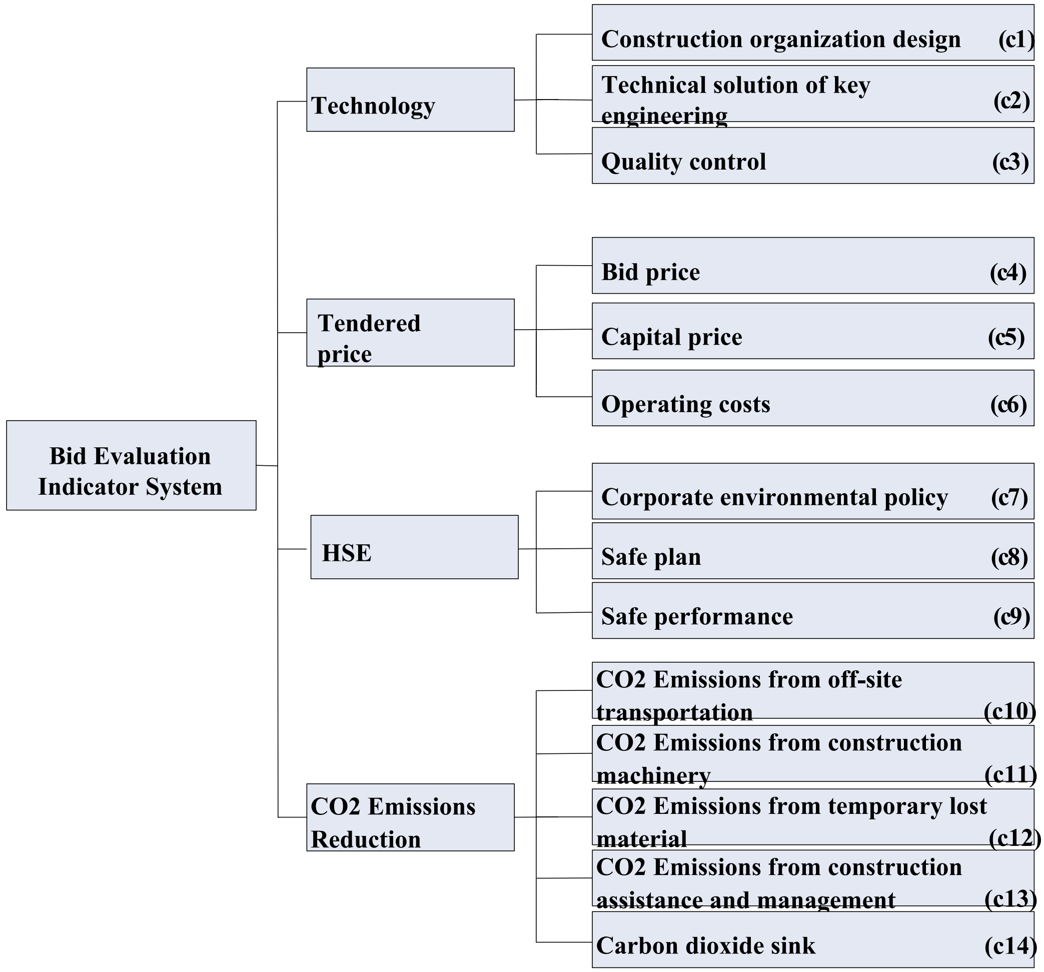

Fig. 2. Formulation of a project bid evaluation system considering carbon dioxide emissions reduction.

indicator system from the literature review and the carbon emissions indicator for the construction phase, a bid evaluation indicator system for public projects considering CO_2 emissions reduction is established. On this basis, a conceptual computational model for CO_2 emissions in the construction phase is developed according to the computing method of the Intergovernmental Panel on Climate Change (IPCC). Because it is difficult to compute the quantity of CO_2 emissions, this study cannot specifically compute the amount of CO_2 emissions of each carbon emissions indicator; it only proposes a conceptual computational model of CO_2 emissions. In other words, the indicator of CO_2 emissions reduction should be considered in the bid evaluation stage in mega public projects, and it can have a guiding effect on contractors, spurring them to improve their construction technology and scheme and to make their construction process green, energy saving and sustainable. This section mainly covers the following three topics: (1) the analysis of the advantage of the linguistic group decision-making model for bid evaluation; (2) the conceptual computational model of CO_2 emissions reduction; and (3) the linguistic group decision-making model.

3.1. Analysis of the advantages of the linguistic group decisionmaking model for bid evaluation

In the process of bid evaluation, many indicators and many experts are involved, in addition to the inherent uncertainty of construction projects. Therefore, bid evaluation is actually a complex multi-attribute group decision-making problem. In real group decision problems, there exist qualitative indicators and quantitative indicators. Some qualitative indicators can be measured as quantitative values, whereas others, such as safety performance and a safety plan in the bid evaluation indicator system in this study, cannot. Decision makers can merely assess these indicators qualitatively, and the most appropriate expression is the linguistic term. Given the difficulty of quantifying many indicators in the bid evaluation indicator system, this study proposes a linguistic group decision-making model for bid evaluation. Compared with existing bid evaluation methods (such as the fuzzy bid evaluation method, cluster analysis, the multi-attribute utility method, neutral networks, and AHP), the advantages of the linguistic group decision-making model are as follows: (1) it is easy to for people to grasp and utilize to calculate the final score of the alternatives; (2) it allows experts to express their opinions about the performances of indicators in a more realistic manner because the use of the linguistic group decision-making model facilitates performing the assessment in qualitative and linguistic or approximate terms that better correspond to real-world situations; and (3) it includes a determination model of the expert's weight, a determination model of the indicator's weight and an information aggregation model. This type of model is in line with people's decision-making habits and can aggregate all of the experts' decision-making information. Therefore, it can avoid the bias of the individual expert and ensure the rationality of the result.

3.2. Conceptual computational model for CO_2 emissions reduction in the construction phase

The IPCC has condensed a significant amount of research into three methods for computing CO_2 emissions. The first method is used to compute the emissions from fuel combustion and estimates the average emissions factor and the amount of combustion. The emissions factor is estimated from the carbon content of the different fuels. In practice, this method produces an average CO_2 emissions factor that is inaccurate because of the variation in technologies and combustion equipment. Therefore, the second computation method is proposed on the basis of the first method and is applied to calculate the CO_2 emissions by using the emissions factor of a specific country. However, different countries have different fuel types, combustion techniques and factory facilities; consequently, the IPCC has developed a third method with which CO_2 emissions can be estimated according to different factory techniques, facilities and fuel sources. The relevant available data show that the first and second methods are widely used (Liu et al., 2010). The specific estimation process consists of six steps as follows:

Step 1: estimate the amount of fuel consumption; Step 2: transform the amount of fuel consumption into a universal unit for energy;

Step 3: calculate the total quantity of CO_2 emissions corresponding to the carbon content per unit of energy; Step 4: calculate the amount of incombustible carbon; Step 5: correct the quantity of unoxidized carbon according to the oxygenation efficiency; and

Step 6: transform the quantity of carbon that is emitted into CO_2 emissions.

In this study, five computational formulas for the various carbon sources (i.e., equations (1)e(5)) and an overall conceptual computational model for CO_2 emissions (i.e., equation (6)) are developed based on the CO_2 emissions indicator system for the project construction phase established in Section 2.2. These formulas are shown below.

1. CO_2 emissions from construction machinery (E_{c1})

Let $T_k (k = 1, 2, \ldots, K_1)$ denote the time period during which the K^{th} type of construction machinery is used; let $e_{jk} (j = 1, 2, \ldots, J)$ denote the consumption of the jth type of energy by the K^{th} type of construction machinery; and let x_j denote the CO_2 conversion coefficient for various types of fuels. Then, the amount of CO_2 emissions from the construction machinery is given by the following equation (Eq. (1)):

$$E_{c1} = \sum_{k=1}^{K_2} \sum_{j=1}^{J} x_j e_{jk} T_k \quad (1)$$

2. CO_2 emissions from off-site transportation (E_{c2})

Let $g_k (k = 1, 2, \ldots, K_2)$ denote the correction coefficient of the road condition for the K^{th} type of transportation equipment. The values of the correction coefficient vary considerably with the different road conditions for highway transport but vary only slightly for water transport, railway transport and air transport. Let $e_{ijk} (i = 1, 2, \ldots, I; j = 1, 2, \ldots, J)$ denote the consumption of the jth type of fuel by the K^{th} type of transportation to produce a unit amount of the ith type of construction material; let Q_{ik} denote the quantity of the ith type of construction material transported by the K^{th} type of transportation equipment; let D_{ik} denote the distance of the ith type of construction material transported by the K^{th} type of transportation equipment; and let x_j denote the conversion coefficient of CO_2 for various types of fuels. The CO_2 emissions from offsite transportation are then given by

$K_1 \quad I \quad J$

$$E_{c2} = \sum_{k=1}\sum_{i=1}\sum_{j=1} g_k x_j e_{ijk} Q_{ik} D_{ik} \qquad (2)$$

3. CO_2 emissions from the consumption and loss of temporary construction material (E_{c3})

Let $e_{1j} (j = 1, 2, \ldots, J)$ denote the consumption of the jth type of fuel used for permanent construction material; let $e_{2j} (j = 1, 2, \ldots, J)$ denote the jth type of fuel consumed for the amortization of temporary construction measures material; let $e_{3j} (j = 1, 2, \ldots, J)$ denote the consumption of the jth type of fuel consumed by temporary materials; and let x_j denote the conversion coefficient of CO_2 for various types of fuels. The CO_2 emissions from the consumption of temporary construction materials are then given by

$$E_{c3} = \sum_{j=1}^{J} x_j \left(e_{1j} + e_{2j} + e_{3j}\right) \qquad (3)$$

4. CO_2 emissions from construction assistance and construction management activities (E_{c4})

Let El_1 denote the quantity of electricity consumption of nighttime construction lighting; let El_2 denote the quantity of electricity consumption associated with construction management material; let El_3 denote the quantity of electricity consumption associated with construction management equipment; and let x_{El} denote the conversion coefficient of CO_2 for various types of fuels. The CO_2 emissions from construction assistance and construction management activities are then given by

$$E_{c4} = x_{El}(El_1 + El_2 + El_3) \quad (4)$$

5. Construction carbon sink (E_{c5})

Let S denote the area for forestation measures; let $e_j (j = 1, 2, \ldots, J_0)$ denote the consumption of the jth type of green fuel; let z denote the carbon sink coefficient of the forestation measures; and let 2_j denote the carbon sink coefficient for the quantity of the jth type of green fuel consumed. The construction carbon sink is then given by

$$E_{c5} = S \cdot z + \sum_{j=1}^{J_0} 2_j e_j \quad (5)$$

6. Overall conceptual computational model of CO_2

The computational formulas for the various CO_2 emissions sources can be combined to produce the following overall conceptual computational model for CO_2 emissions:

$$E_c = E_{c1} + E_{c2} + E_{c3} + E_{c4} + E_{c5} = \sum_{k=1}^{K_1}\sum_{i=1}^{I}\sum_{j=1}^{J} g_k x_j e_{ijk} Q_{ik} D_{ik} + \sum_{k=1}^{K_2}\sum_{j=1}^{J} x^j e_{jk} T_k + \sum_{j=1}^{J} x^j (e1^j + e2^j + e3^j) + x_{El}(El1 + El2$$

J0

þ El3Þþ S$zþX2jej

j¼1

(6)

This conceptual computational model is only associated with the construction phase, and the carbon emissions in the life cycle period of the public project will be investigated in further studies.

3.3. Linguistic group decision-making model

The linguistic group decision-making model in this study consists of the determination model of the indicator weights, the determination model of the expert weights and the information aggregation model. In the decision-making process, the experts can assess one alternative in terms of each bid evaluation indicator by using a scale ranging from 1 to 7. In terms of the indicators of CO_2 emissions reduction, the conceptual computational model is obtained only from this study. Given the difficulty in precisely computing the amount of CO_2 emissions, these indicators are also assessed with linguistic terms. Linguistic terms such "good" and "very good" correspond to different linguistic values, and the specific matching rule in this study uses a scale ranging from 1 to 7: 1 (slightly poor), 2 (fair), 3 (slightly good), 4 (good), 5 (very good), 6 (extremely good) and 7 (excellent). Then, according to this assessment information, entropy and relative entropy are used to determine the indicator weights, the standard deviation is applied to determine the expert weights, and the information aggregation model is utilized to aggregate the assessment information. Finally, the comprehensive scores of all alternatives can be obtained to rank the alternatives in order of preference. The specific description of the linguistic group decision-making model and some basic definitions are given below.

Consider S experts such that $E = \{e_1; e_2; \ldots; e_s\}$ denotes the expert set. Let the alternative set and the attributes set be denoted by $X = \{x_1; x_2; \ldots; x_n\}$ and $C = \{c_1; c_2; \ldots; c_m\}$, respectively; the expert weight vector is denoted by $x = (x_1; x_2; \ldots; x_s)^T$, where $0 \le x_k \le 1; k = 1; 2; \ldots; s$ and $\sum_{k=1}^{s} x_k = 1$. The indicator weight is denoted by $u = (u_1; u_2; \ldots; u_m)^T$, where $0 \le u_j \le 1; j = 1; 2; \ldots; m$ and $\sum_{j=1}^{m} u_j = 1$. The expert e_k evaluates the alternative x_i in terms of the attribute C_j to obtain a linguistic score decision matrix of the alternatives with the indicator $A_k = (a^k_{ij})_{nm}$, where $k = 1, 2 \ldots s$; $i = 1, 2 \ldots n$; and $j = 1,2 \ldots m$. The expert evaluates the alternatives using a scale ranging from 1 to 7.

Definition 1 (Wei et al., 1999) Suppose that $x_i; y_i \ge 0$; $i = 1; 2; \ldots; n$ and $1 = \sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i$; thus, we designate

$$h(X;Y) = \sum_{i=1}^{n} x_i \log(x_i/y_i)$$

the relative entropy of Y relative to X, where $X = (x_1; x_2; \ldots; x_n)$ and $Y = (y_1; y_2; \ldots; y_n)$. Therefore, the relative entropy can be adopted to measure the coincidence of X and Y.

3.3.1. Determination model for the indicator weights

(1) Obtain the indicator objective weights using entropy

The indicator is evaluated by an expert using a seven-point scale (which corresponds to the natural numbers from 1 to 7); therefore, the score matrix does not need to be standardized. For the ith alternative, the entropy of every indicator can be obtained from the linguistic score information given by the experts, which can be represented as Eq. (7) according to definition 1.

s

Hji ¼ kXpkij ln pkij (7)

k¼1

where k ¼ 1=ln s and pkij ¼ aijk=Pni¼1akij.

According to the definition of entropy, the smaller the difference in the unidentified information is, the greater the entropy and the better it is for decision-making. Therefore, entropy is defined by the smaller weight value:

i ¼ 1 Hji (8) uj m i m Pj¼1 Hj

Thus, we can obtain the objective weights of the indicators from the judgment information of the ith alternative, i.e., u$^{i}_{j}$ ¼ ðu$^{i}_{1}$;u$^{i}_{2}$;::::;u$^{i}_{m}$Þ. The objective indicator weights of all of the alternatives can then be used to compose the weight matrix as follows:

$\begin{pmatrix} 1 & & m \\ \vdots & \ddots & \vdots \\ n & & n \\ & & m \end{pmatrix}$ ∧ u1 / u1

u ¼(9) u$_{1}$ / u

(2) Obtain the indicator optimal weight using the relative entropy

Based on the literature (Qian et al., 1991), we consider that x$_{i}$; y$_{i}$ 0; i ¼ 1; 2;:::; n and 1 ¼ P$^{n}_{i¼}$1x$_{i}$ P$_{i}^{n}$$_{¼}$1y$_{i}$; thus, hðX; YÞ is the relative entropy of X to Y:

n

hðX;YÞ ¼$x_i$lgðx_i=y_iÞ (10)

i

where X ¼ ðx_1; x_2;::::; x_nÞ and Y ¼ ðy_1; y_2;::::; y_nÞ. Therefore, we can use the relative entropy to measure the coincidence of X and Y.

Let the optimal weight of the indicator be denoted by u ¼ ðu_1;u_2;:::u_mÞ; then, each line of the matrix can be viewed as a distribution of the indicator weight rates given by all of the experts for each alternative. The definition of relative entropy shows that a smaller difference between the relative entropy and the optimal indicator weight distribution is better. Thus, the optimal model can be expressed as follows: minREð^{u}Þ ¼ PP$u_j$lg _ui$_{jj}$! n m u

i¼1 $_j$¼1

m (11) s:t u_j ¼ 1;u_j >0 jP¼1

j ¼ 1;2;:::;m

Then, the overall optimum solution of the model, i.e., the optimum weight u* ¼ ðu$^*_1$;u$^*_2$;:::;u$^*_m$Þ of the indicators, is given by

u*$_j$ ¼ Yui$_j$'XYui$_j$;j ¼ 1;2;…m (12) n m n

i¼1 j¼1 i¼1

3.3.2. Determination model for the expert weights using the standard deviation

For an indicator c_j and an expert e_k, the standard deviation between the alternative x_i and all of the other alternatives can be represented as follows:

Skj ¼ sTnXXni¼1akijxk 1_sXffi st¼1atjkxk2ffi (13)

–

¼ xkr1nni¼1 ak akj 2;k ¼ 1;2;:::; s

d ij;

where akj ¼ 1nPnit¼1aktj represents the average value of an expert forkij kj kij kj kj m indicators. The term dða ; a Þ ¼ a a (Xu, 2007; Xu and Da, 2011) represents the deviation of mean value a from the indicator values akij of the alternative xi for the expert ek and the indicator cj.

Thus, Skj denotes the standard deviation for the expert ek of the indicator cj.

The aforementioned analysis can be used to choose the weight vector x such that the standard deviation values are maximized for all of the indicators and all of the experts. This objective can be accomplished using the following model:

m s

max FðxÞ ¼ jP¼1uj jP¼1Skj (14)

¼ jP¼m1 – kP¼s1 r1Xn k akj 2ffi; uj xk n i¼1 d aij;

s

s:t: Xx2k ¼ 1; xk 0

k¼1

Let sjk ¼ r_n1Xin¼1dakij; akj 2ffi (15)

Then, the aforementioned model can be transformed as follows:

m s

8>>><max Fðx Þ ¼ jP¼1uj kP¼1xkskjs (16)

≥

>:s:t: xk 0 k ¼ 1;2;:::s; Xx2k ¼ 1 :

k¼1

A Lagrange function can be formed using the results from the literature review (Xu and Da, 2011):

m k

xk ¼ j¼1ujsj 2 (17) s Pm k!ffi utPk¼1 j¼1ujsj

By normalizing xk to let the sum of xk, j ¼ 1; 2;:::s; be unity, we obtain the following:

m

xk ¼ Psk¼k1xk ¼ Pmj¼P1u¼j Pks¼1skj ; k (18)∗ x j 1ujskj

¼ 1;2;:::;s

m (19)

Let Dk ¼ Xujskj ;k ¼ 1;2;:::;s

j¼1 Pk¼1 Dk

Then; x*k ¼ sDk ; k ¼ 1;2;:::;s (20)

The term Dk represents the standard deviation of all alternatives for the expert ek and for all of the indicators. A larger value of Dk indicates that expert e_k is more important. Eq. (20) is directly obtained by dividing each D_k by the sum of the D_k values. This method is based on information theory; that is, a larger weight is assigned to the expert who provides more information.

3.3.3. Information aggregation model

The optimal weight of each indicator u^*_j and the weight of each expert x^*_k can be obtained from Sections 3.3.1. and 3.3.2. The traditional linear weighting method is used to calculate the comprehensive score for each alternative. The total indicator information aggregation of the ith alternative for the expert K is given by

$$\tilde{S}_{ki} = \sum_{j=1}^{m} a_{kij} u^*_j \quad (21)$$

The formula for the information aggregation of all of the experts for the ith alternative (i.e., the final score for each alternative) is

$$S_i = \sum_{k=1}^{s} \tilde{S}_{ki} x^*_k \quad (22)$$

4. Linguistic group decision-making framework for bid evaluation of mega public projects considering CO_2 emissions reduction

Entropy, relative entropy, the standard deviation method and the weighted aggregation operator are used in the linguistic group decision-making process to evaluate bids for a mega public project considering CO_2 emissions reduction; there are seven main steps in the specific bid evaluation framework, which are shown in Fig. 3.

Step 1. Establishment of the bid evaluation committee.

The bid evaluation committee refers to the temporary authority of the tenderee and the technical and economic experts who are responsible for the evaluation of the bid documents and put forwarding comments on the bidding documents. When organizing the tendering activities, the technical and economic management experts of the bid evaluation committee shall be randomly selected by the tenderee under the supervision of the engineering bidding office and through the computer software, lotting numbers, drawing lot and so on. In this study, we also need a environmental expert for the purpose of evaluating the CO_2 emission. The number of the selected tender for approval in the tender documents will be authorized by the office of the project validation. The bid evaluation committee consists of the representative of the owner and experts in economic, technical and other areas. The number of committee members should be an odd number and no less than 5; the experts in technical and economic area shall not be less than two-thirds of the total number of members. The specific number of experts should depend on the complexity of the project.

Step 2. Preliminary evaluation of the bids.

The major tasks in the preliminary review are as follows: checking the completeness of the bids offered by each bid unit; rechecking the quotations for each bid unit; modifying the arithmetic mistakes in the bids; approving bids with non-essential deviations from the bid terms; eliminating bids with essential deviations from the bid terms; and determining the list of bidders that are subject to a detailed review.

Step 3. Establishment of an indicator system for bid evaluation.

The indicator system is based on the literature review discussed above and consists of the technology, the tendered price, the HSE and the CO_2 emissions reduction (where indicators can be added or deleted, depending on the complexity of the specific project); Fig. 2 shows the details of the indicator system.

Step 4. Completion of a bid matrix table for detailed evaluation by expert assessment.

Fig. 3 shows how the bid evaluation indicator system is used by the bid evaluation committee to assess the indicators on a scale ranging from 1 to 7: 1 (slightly poor), 2 (fair), 3 (slightly good), 4 (good), 5 (very good), 6 (extremely good) and 7 (excellent). The assessment result of the indicators that are graded by the experts form the matrix table in the bid evaluation.

Step 5. Determination of the indicator weights using entropy and relative entropy.

Obtain the objective weight of the indicator using entropy.

The entropy of each indicator H_j^i is calculated using Eq. (7), and the entropy value of each indicator w^i_j is calculated using Eq. (8).

Obtain the optimal weight of the indicator using relative entropy.

Eq. (12) is used to calculate u_j ðj ¼ 1; 2;:::; mÞ for each indicator.

Step 6. Determination of the expert weights using the standard deviation.

Eq. (13) is used to calculate the standard deviation S^k_j ; Eqs. (15)e(20) are then used to calculate the final expert weight x^*_k.

Step 7. Obtain the final score of each alternative and prioritize the alternatives.

Eq. (21) is used to calculate the score of the indicator aggregation $\sim S^k_i$ of each alternative x_i; Eq. (22) is then used to calculate the final score of the expert aggregation S_i of each alternative x_i, and the scores are prioritized to select the winning bidder.

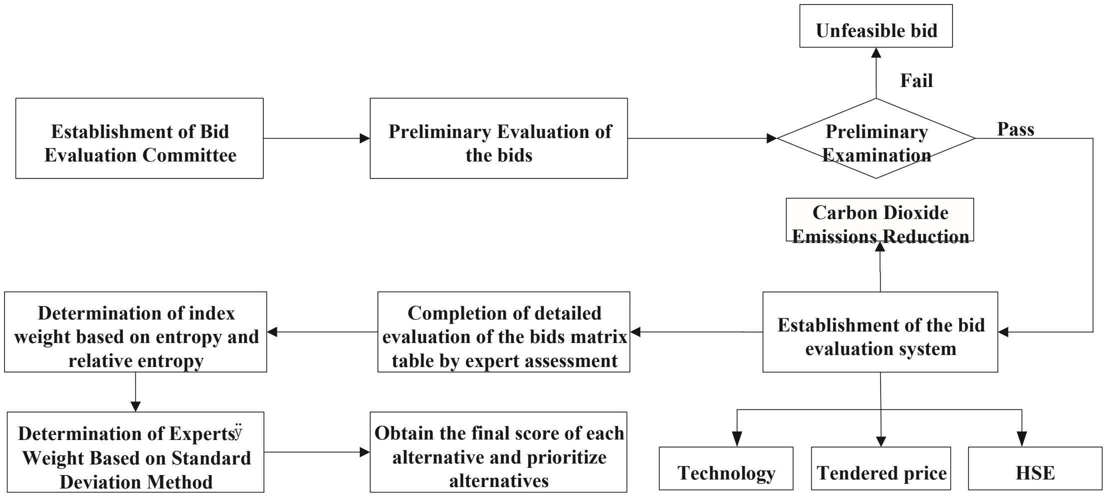

Fig. 3. Bid evaluation flow chart considering carbon dioxide emissions reduction.

5. A case study and comparison with a scenario

The linguistic group decision-making framework for the bid evaluation established above is validated by application to an important hydropower station program decision-making process. The results of the bid evaluation framework considering and not considering CO_2 emissions reduction are compared to show that incorporating CO_2 emissions reduction into the bid evaluation is scientifically based and environmentally beneficial.

5.1. Case study for bid evaluation considering CO_2 emissions reduction

Hydropower station A is located in Sichuan Province, Aba Zang and Qiang minority Autonomous Prefecture, Heishui County, China; water flows into the station from Hongyan village at the middle reach of the Heishui River to the Eshiba River; the station is the three-step hydropower station on Heishui River for the second dam of the five-grade plan. The station is a two-diversion, single hydropower station. The station uses the mixing tap method, for which the first hub consists of a water-holding construction, a spillway, and an emptying tunnel. The dam is constructed with a gravelly soil vertical core rockfill wall; the crest elevation is 2138.00 m, the dam width is 12.0 m, and the maximum dam height is 147.00 m. An open spillway is located at the left shoulder of the dam and has an overall length of 532 m. The emptying tunnel is located on the left side of the riverway and has an overall length of 1145.51 m. The project subject to tender is the construction work of the #1 and #2 gully management works; the main project work includes (but is not limited to) the following tasks: (1) the general project work (which is temporary in nature), (2) the management of gully #1 and (3) the management of gully #2. The work for the tender is as follows: the earthwork open excavation: 462.91 m^3; the anchor cable: 91 roots; the anchor bars: 249 roots; the rock bolt: 35 roots; the SNS passive safety net: 120 m^2; the frame beam concrete: 1038 m^3; the wall concrete: 447.82 m^3; and 70 tons of steel fabrication and installation. The project is a typical mega public project. The owner published the call for tenders on the internet for the Sinohydro Group Ltd., the China Hydropower Construction Group and the Sichuan Electric Power Development Co., Ltd. Ten excellent contracting enterprises responded to the bid; the specific bid evaluations are given below.

Step 1. Establishment of a bid evaluation committee.

According to the specific characteristics of the project, the owner hired seven experts in the areas of finance, technology, economics and energy to constitute the bid evaluation committee (the number of experts was determined by the complexity of the project).

Step 2. Preliminary evaluation of the bids.

Through the preliminary evaluation of the bids, 5 enterprises with essential deviations from the bid terms were disqualified; the remaining 5 enterprises passed the preliminary evaluation and had access to the detailed bid evaluation.

Step 3. Establishment of the indicator system for bid evaluation.

The main indicators used in the aforementioned literature review were the technology, the tendered price, the HSE and CO_2 emissions reduction; details are presented in Fig. 2.

Step 4. Completion of the bid matrix table for detailed evaluation by expert assessment.

Fig. 3 shows how the bid evaluation committee used the bid evaluation indicator system to assess the indicators on a scale ranging from 1 to 7. The expert assessment was used to establish the indicator matrix table Ak ¼ ðakijÞnm at the bid evaluation stage as follows:

B

7 5 5 3 7 2 2 7 6 5 2 6 3

A1¼BBBBB@x23

4 3 6 3 2 2 6 5 7 6 1 2 3

1 6 2 2 2 1 3 7 6 7 1 4 5

x4 x5

224

CCCCCCA

O x1 6 5 4 5 4 2 5 5 4 4 4 7 4 1 c1 c2 c3 c4 c5

c6 c7 c8 c9 c10 c11 c12 c13 c14

x 4 2 2 2 3

3 2 4 4 4 3

3 4 5

B

5 2 6 3 6 3 4 5 4 3 3 1 2

A2¼BBBBB@x23

5 4 4 1 3 3 4 6 5 3 1 3 4

5 2 5 2 2 3 5 1 5 1 2 4 6

x4 x5

336

CCCCCCA

O x1 4 7 3 6 6 2 4 6 4 7 6 3 6 3 1 c1 c2 c3 c4 c5

c6 c7 c8 c9 c10 c11 c12 c13 c14

x 5 6 5 2 2

2 5 3 5 2 1

2 3 2

B

4 5 5 4 4 2 2 3 6 2 2 2 3

A3¼BBBBB@x23

2 7 4 2 4 2 5 2 7 2 2 2 3

2 5 5 3 3 2 4 6 6 2 3 7 5

x4 x5

222

CCCCCCA

O x1 6 6 7 5 5 4 2 7 6 6 4 4 4 4 1 c1 c2 c3 c4 c5

c6 c7 c8 c9 c10 c11 c12 c13 c14

x 4 5 5 3 3

2 6 4 5 2 3

3 4 2

B

A4¼BBBBB@x23 6 2 7 5 5 2 4 7 4 2 1 3 4 / 6 6 2 2 5 2 2 6 6 2 3 2 3 / 4 4 2 2 3 2 2 4 4 3 2 7 4 2 24 CCCCCCA

x4 x5

O x1 2 2 5 4 4 2 6 2 7 5 5 5 5 4 1 c1 c2 c3 c4 c5

c6 c7 c8 c9 c10 c11 c12 c13 c14

x	4	2	6	2	2
1	4	2	4	1	2
2	3	2			

O x1 4 6 6 5 7 3 6 3 6 6 6 5 6 3 1 c1 c2 c3 c4 c5 c6 c7 c8 c9 c10 c11 c12 c13 c14

B B A5¼BBBxx23 52 66 56 55 36 32 76 55 64 23 31 23 34 24

CCCCCCA

B@x5 1 7 7 3 3 2 7 5 7 2 3 6 5 7 x4 2 2 6 2 1 1 6 5 5 1 2 1 2 1

B

A6¼BBBBB@x23 5 3 2 4 3 4 3 3 2 5 6 6 7 / 2 6 5 6 2 4 4 6 2 2 1 4 2 / 5 5 4 3 3 3 4 3 2 6 2 5 4 5 15 CCCCCCA

x4 x5

O x1 4 5 4 4 5 2 5 5 5 5 5 4 3 5 1 c1 c2 c3 c4 c5

c6 c7 c8 c9 c10 c11 c12 c13 c14

x	6	4	3	6	4
4	5	3	3	5	5
6	5	3			

B

A7¼BBBBB@x23 6 5 4 5 4 3 2 2 1 4 6 6 6
4 3 3 2 5 3 6 1 5 3 3 6 2 6 16
3 3 2 5 5 2 5 6 2 2 2 3 7 CCCCCCA
x4 x5

O x1 5 6 3 7 6 3 4 6 5 4 4 5 4 6 1 c1 c2 c3 c4 c5

c6 c7 c8 c9 c10 c11 c12 c13 c14

x 2 3 6 4 5

2 4 2 6 4 4

4 6 5

Step 5. Determination of the indicator weights based on entropy and relative entropy.

(1) Obtain the indicator objective weights using entropy

Eq. (7) was used to calculate the entropy H_j^i of the indicators of the five alternatives, as shown in Table 2.

Eqs. (8) and (9) were used to calculate the entropy w^i_j of the indicators, as given below.

$$\hat{w} = \begin{pmatrix} 0.1047 & 0.1065 & 0.1033 & 0.0407 & 0.0428 & 0.0735 & 0.1012 & 0.1434 & 0.0428 & 0.0428 & 0.0259 & 0.0311 & 0.0789 & 0.0625 \\ 0.0456 & 0.0948 & 0.0618 & 0.1050 & 0.0545 & 0.0807 & 0.0608 & 0.0562 & 0.0236 & 0.1109 & 0.1109 & 0.0785 & 0.0314 & 0.0853 \\ 0.0416 & 0.0613 & 0.0450 & 0.0166 & 0.0280 & 0.0303 & 0.0673 & 0.0670 & 0.0917 & 0.0575 & 0.2075 & 0.1294 & 0.0679 & 0.0890 \\ 0.0757 & 0.0690 & 0.0464 & 0.1225 & 0.0973 & 0.0606 & 0.0414 & 0.0989 & 0.0401 & 0.0636 & 0.0697 & 0.1172 & 0.0277 & 0.0700 \\ 0.1523 & 0.0633 & 0.1060 & 0.0540 & 0.0437 & 0.0462 & 0.0600 & 0.1038 & 0.0951 & 0.1807 & 0.0182 & 0.0403 & 0.0178 & 0.0187 \end{pmatrix}$$

Table 2
The indicator entropy value H_j^i for the five alternatives.

Alternatives	Indicator entropy value H_j^i
1	HH18 1 ¼¼ 1 :9761; H2 1 1 ¼ 00::97579903;; HH3 10 1 1 ¼1¼00:9764:9903;;HH41 11 1¼1¼0:09907:9941; H;51H12¼1 0¼:99030:9929; H61; H¼13 1 0¼:98320:9820; H71;¼H14 10:9769¼ 0:9857; 1 0:9673; H9 ¼
2	HH18 2 ¼¼ 0:9793; H2 2 2 ¼ 00::95699893;; HH3 10 2 2 ¼1¼00:9719:9496;;HH42 11 2¼1¼0:09523:9496; H;52H12¼2 0¼:97520:9644; H62; H¼13 2 0¼:96340:9857; H72;¼H14 20:9724¼ 0:9613; 2 0:9745; H9 ¼
3	HH18 2 3 ¼¼ 00::97339570;; HH2 9 3 3 ¼¼ 00::94119606;; HH10 3 3 3 ¼1¼00:9711:9631;;HH43 11 3¼1¼0:09893:8667; H;53H12¼3

[1] :8944 4:5607 2:2804 3:8471 4:0988 0:8944 1:0954 4:3359 1:0954 4:5607 4:1473 2:2804 3:5777 3:03321 4:6043 3:2863 3:5777 2:4495 4:1473 1:4142 3:6332 2:6833 2:6077 2:6077 3:0332 2:9665 3:3466 2:6833
B3:3466 1:7889 2:6077 2:2804 1:6733 1:7889 3:5777 4:1473 1:4142 3:5777 1:6733 4:1473 1:6733 2:8284CCCCCCCCA s_j^k ¼BB3:3466

3:5777 4:6043 2:8284 2:6077 0:8944 3:3466 4:5607 2:8284 3:0332 3:0332 4:3359 1:6733 2:1909

[2] :2863 3:8987 1:4142 2:8284 4:8990 1:6733 1:0954 1:7889 2:2804 3:8471 3:7417 4:1473 3:1623 4:6043

@BBB3:0332 2:2804 2:2804 2:6833 2:2804 1:7889 1:6733 2:8284 2:6077 3:0332 4:3359 2:0000 3:8471 3:5777

[3] :1623 2:8284 3:0332 3:6332 1:4142 1:0954 2:9665 4:8166 4:3359 1:7889 2:9665 2:6077 4:0000 4:3359

0¼:98200:9169; H63; H¼133 0¼:98050:9564; H73;¼H1430:9568¼

0:9429;

4 HH14 ¼ 0:9543; H244 ¼ 00::97589583;; HH31044

¼1¼00:9719:9616;;HH44114¼1¼0:09260:9579; H;54H12¼4 0¼:94130:9292;

H64; H¼134 0¼:96340:9832; H74;¼H1440:9750¼ 0:9577; 4

8 ¼ 0:9403; H9 ¼

5 HH185 ¼¼ 0:9204; H255 ¼ 00::96699503;; HH31055

¼1¼00:9446:9057;;HH45115¼1¼0:09718:9905; H;55H12¼5

0¼:97720:9790; H65; H¼135 0¼:97590:9907; H75;¼H1450:9687¼

0:9903;

(2) Obtain the optimal weights of the indicators using relative entropy

Eq. (12) was used to calculate the following results:

4:695 5:345 5:766 3:416 4:734 4:646 3:2841

O 3:497 3:691 2:456 4:584 4:272 5:061

3:151 3:789 3:163 4:409 3:956 3:891 3:951CC

~Si k ¼

BB4:886

50:9458; H9 ¼

B
@

3:609 4:193 3:124 4:188 3:036

4:117 2:914CCA B3:928 2:622

4:304 3:647 4:546 4:212 3:784

---

u^*_1 ¼ 0:111;u^*_2 ¼ 0:131;u^*_3 ¼ 0:068;u^*_4 ¼ 0:023;u_5^* ¼ 0:013;u^*_6 ¼ 0:024;u^*_7 ¼ 0:050; u^*_8 ¼ 0:268;u^*_9 ¼ 0:017;u^*_{10} ¼ 0:152;u^*_{11} ¼ 0:023;$^{u}{}_{12}{}^*$ ¼ 0:072;u^*_{13} ¼ 0:004;u^*_{14} ¼ 0:030

Step 6. Determination of the expert weights using the stan- Eq. (22) was used to calculate the final score of the expert agdard deviation. gregation S_i of each alternative x_i.

Eq. (15) was used to calculate s^k_j, as given below.

O

B

Eq. (19) was used to calculate the standard deviation D_k, as given below:

D_1 ¼ 2:5212; D_2 ¼ 2:7067;D_3 ¼ 2:8404;D_4 ¼ 3:0342;D_5 ¼ 2:3283;D_6 ¼ 2:2915;D_7 ¼ 2:7841

Eq. (20) was used to calculate the final expert weight x^*_k, as given below.

x^*_1 ¼ 0:136;x^*_2 ¼ 0:146;x^*_3 ¼ 0:153;x^*_4 ¼ 0:164;x_5^* ¼ 0:126;x^*_6

¼ 0:124;x^*_7 ¼ 0:150

Step 7. Obtain the final scores for the alternatives and prioritize the alternatives.

Eq. (21) was used to calculate the indicator aggregation score $\sim S^k_i$ of each alternative x_i.

S_1 ¼ 4:7925; S_2 ¼ 3:5065; S_3 ¼ 3:9983; S_4 ¼ 3:5980; S_5

¼ 3:8363

Finally, the scores were used to prioritize the alternatives as follows: x_1_x_3_x_5_x_4_x_2; the highest score corresponded to x_1, which was selected as the winning bid.

5.2. A comparison with a traditional bid evaluation scenario: not considering CO_2 emissions reduction

If CO_2 emissions reduction is not considered in the bid evaluation, then the indicators for the bid evaluation will only consist of the technology, the tendered price and the HSE. In this case, based on the expert assessment of the aforementioned alternatives (i.e., the test basis is the same as the original assessment), the aforementioned bid evaluation steps are used to re-compute the final score for each alternative.

Step 4. Expert assessment without CO_2 emissions reduction.

Using the assessment matrix A_k in step 4 in Section 5.1 as the basis, the indicators associated with CO_2 emissions reduction were removed and the matrix table was obtained without considering CO_2 emissions reduction. The first expert's scores for the nine indicators for the five alternatives are given below.

O x1 6 5 4 5 4 2 5 5 4 1 c1 c2 c3 c4 c5 c6 c7 c8 c9

B B · Bx2 4 2 2 2 3 3 2 4 4 CCCCCCA

A1 ¼ BBx3 7 5 5 3 7 2 2 7 5 B@x4 4 3

6 3 2 2 6 5 6 x5 1 6 2 2 2

1 3 7 7

The assessments of the five alternatives by the other experts were similarly obtained and are not listed here because of space limitations.

Step 5. Determination of the indicator weights using entropy

and relative entropy.

(1) Obtain the objective weights using entropy

i for the five alterEq. (7) was used to calculate the entropy H_j

natives, as shown in Table 3 below.

i of each Eqs. (8) and (9) were used to calculate the

entropy w_j indicator; the objective entropy values of each alternatives were

∧

then used to compose the weight matrix w :

$$\begin{pmatrix} 0.1379 & 0.1403 & 0.1361 & 0.0536 & 0.0563 & 0.0968 & 0.1334 & 0.1890 & 0.0563 \\ 0.0782 & 0.1627 & 0.1060 & 0.1801 & 0.0935 & 0.1384 & 0.1043 & 0.0964 & 0.0405 \\ 0.0926 & 0.1365 & 0.1002 & 0.0371 & 0.0624 & 0.0675 & 0.1500 & 0.1493 & 0.2043 \\ 0.1160 & 0.1059 & 0.0713 & 0.1879 & 0.1492 & 0.0930 & 0.0635 & 0.1517 & 0.0615 \\ 0.2103 & 0.0874 & 0.1463 & 0.0745 & 0.0603 & 0.0638 & 0.0828 & 0.1433 & 0.1312 \end{pmatrix} \wedge$$

w ¼

(2) Obtain the optimal weights of the indicators using relative entropy

Eq. (12) was used to calculate the optimal weight of each indicator as follows:

u^*_1 ¼ 0:157; u^*_2 ¼ 0:186;u^*_3 ¼ 0:097;u^*_4 ¼ 0:032;u^*_5 ¼ 0:019; u^*_6 ¼ 0:035;u^*_7 ¼ 0:071;u^*_8 ¼ 0:380; u^*_9 ¼ 0:024

Step 6. Determination of the expert weights using the standard deviation method.

k, as given below.

Eqs. (13)e(15) were used to calculate s_j

Eq. (19) was used to calculate the standard deviation D_k, as given below.

D_1 ¼ 1:7051; D_2 ¼ 1:5906; D_3 ¼ 1:8446; D_4 ¼ 1:0763;

D_5 ¼ 1:1557; D_6 ¼ 1:4033; D_7 ¼ 2:0686

*

Eq. (20) was used to calculate the final expert weight x_k.

x^*_1 ¼ 0:144;x^*_2 ¼ 0:086;x^*_3 ¼ 0:100;x^*_4 ¼ 0:112;x^*_5

¼ 0:062;x^*_6 ¼ 0:076;x^*_7 ¼ 0:112

Step 7. Obtain the final scores for the alternatives and prioritize the alternatives.

k –

Eq. (21) was used to calculate the attribute aggregation score S_i

of each alternative

x_i:

4:917 5:292 6:078 2:799 4:434 4:614 2:9351

03:178 4:173 4:235 2:859 5:201 3:952 5:319

B

4:897 2:667

B@4:6452:704 4:563 3:515 4:926 3:833 4:231

B

S^i ¼ B 5:735 4:334 3:646 5:358 4:826

3:263 3:527CCACC _k

4:442 4:795 3:594 5:047 3:832

Eq. (22) was used to obtain the final score of the expert aggregation S_i of each alternative x_i.

S_1 ¼ 3:3057; S_2 ¼ 2:5118; S_3 ¼ 3:1055;S_4 ¼ 28851;S_5

¼ 2:8220

The scores were used to prioritize the alternatives as follows:

x_1_x_3_x_4_x_5_x_2.

5.3. Analysis and discussion of the results

Based on the results of comparing the bid evaluations considering and not considering CO_2 emissions reduction, we can observe that the final priority sequence of the bid evaluation considering CO_2 emissions reduction is x_1_x_3_x_5_x_4_x_2, whereas the final

---

0 0:8944 4:5607 2:2804 3:8471 4:0988 0:8944 1:0954 4:3359 1:09541 4:6043 3:2863

3:5777 2:4495 4:1473 1:4142 3:6332 2:6833 2:6077

sk j ¼ BBBBB333:::346634662863133:::788957778987241:::607760434142

B

222:::280482848284124:::673360778990101:::788989446733331:::577734660954

441:::147356077889122:::280441428284CCCCACCCC

B

B 3:0332 2:2804 2:2804 2:6833 2:2804 1:7889 1:6733 2:8284 2:6077 @3:1623 2:8284

3:0332 3:6332 1:4142 1:0954 2:9665 4:8166 4:3359

Table 3

i for the five alternatives.

The indicator entropy value H_j

Alternative	Indicator entropy value H_j^i				priority
1				1	¼ 0:9903;
	H_{11} ¼ 0:9761; H_2^1	¼ 0:9757; H_3^1	¼ 0:9764; H_4^1	¼ 0:9907; H_5	
	H_{61}			¼ 0:9903	
2	H_{12} ¼ 0:9832; H_7^1	¼ 0:9769; H_8^1	¼ 0:9673; H_9^1		¼ 0:9752;
	2			¼ 0:9523; H_5^2	
3	H_6 ¼ 0:9793; H_2^2	¼ 0:9569; H_3^2	¼ 0:9719; H_4^2	¼ 0:9893	¼ 0:9820;
4	H_{13} ¼ 0:9634; H_7^2	¼ 0:9724; H_8^2	¼ 0:9745; H_9^2	¼ 0:9893; H_5^3	¼ 0:9413;
	3				
5	H_6 ¼ 0:9733; H_2^3	¼ 0:9606; H_3^3	¼ 0:9711; H_4^3	¼ 0:9411	
	H_{14} ¼ 0:9805; H_7^3	¼ 0:9568; H_8^3	¼ 0:9570; H_9^3	¼ 0:9260; H_5^4	¼ 0:9772;
	4				
	H_6 ¼ 0:9543; H_2^4	¼ 0:9583; H_3^4	¼ 0:9719; H_4^4	¼ 0:9758	
	H_{15} ¼ 0:9634; H_7^4	¼ 0:9750; H_8^4	¼ 0:9403; H_9^4	¼ 0:9718; H_5^5	
	5				
	H_6			¼ 0:9503	
	¼ 0:9204; H_2^5	¼ 0:9669; H_3^5	¼ 0:9446; H_4^5		
	¼ 0:9759; H_7^5	¼ 0:9687; H_8^5	¼ 0:9458; H_9^5		

sequence not considering CO_2 emissions reduction is x_1_x_3_x_4_x_5_x_2. Clearly, the priorities in both cases are different. However, the top alternative is the same bidder, most likely because the top contractor is excellent in many or all indicators, i.e., technology, the tendered price, HSE and CO_2

emissions reduction. We can also find that the priority sequences of the other contractors are different. In the previous tables on the expert assessments for each alternative, alternative 5 had a higher score than alternative 4 in the indicators of CO_2 emissions from the consumption of temporary project materials, CO_2 emissions from construction assistance and management activity and the construction carbon sink. Thus, the final score of alternative 5 was higher than that of alternative 4. When the CO_2 emissions reduction was not considered, the opposite prioritized sequence was obtained. Therefore, the final priority sequences considering CO_2 emissions reduction and not considering CO_2 emissions reduction are different.

The practicability and the validity of this new bid evaluation framework are verified through this case study. The contractor or the bidder (i.e., the alternative) with a higher score in CO_2 emissions reduction will have an advantage over other contractors in winning the bid, which indicates that the indicator of CO_2 emissions reduction is an essential indicator whose implication is significant. Considering CO_2 emissions reduction in the bid evaluation stage has a guiding effect on contractors (bidders); therefore, they will devote time and energy to tailoring and improving their construction schemes, use green construction and minimize deleterious environmental effects to cater to the bid evaluation criteria to win the bid. This is especially true in the current economy with global warming, with each country being dedicated to curbing environmental degradation through some public projects. Thus, contractors whose construction technique is more advanced and energy saving are more competitive and have more opportunities to win bids. Simultaneously, considering CO_2 emissions reduction in the bid evaluation stage will prompt the owner to seek and devise a more feasible and impartial bid evaluation mechanism. The vitality of the construction market will be stimulated, and contractors will develop approaches toward health and sustainability.

Moreover, the popularization of this new bid evaluation model considering CO_2 emissions reduction can promote the construction industry to optimize and develop in a technology-intensive and low-energy direction, which will promote the development of green construction. Green construction requires engineering, and enterprises have a higher management requirement, which will stimulate companies to make greater efforts to improve employee quality, adopt innovative management methods, and refine the management process to achieve efficient work. Choosing green construction, construction enterprises can obtain more benefits than traditional construction units in energy conservation, management or technology. The environmental benefits of green construction can be transformed into the social and economic benefits of enterprises.

An important concept that is worth noting here is the carbon credit. On the condition of being authenticated by the reduction organization recognized by the United Nations or European Union, a country or an enterprise reduces carbon emissions by increasing energy efficiency, reducing pollution and reducing development. Therefore, it can obtain a carbon emissions measurement unit that can be used to trade on the carbon trading market. This type of carbon emissions reduction can be measured. For example, if a project uses a new technology and achieves carbon emissions reduction that is greater than that of the original benchmark based on confirmation by the government, then this part of the emissions reduction is a carbon credit. Carbon emissions reduction credit transactions can help meet not only the performance needs of enterprises but also the needs of enterprises and individuals to fulfill their social responsibility. In this study, we do not consider the carbon credit because the current carbon trading market in the construction sector has not been established and the related research on building carbon trading is scarce. Thus, in the future, we will attempt to establish a carbon trading scheme in the construction sector.

6. Conclusions

Implementation of green construction is the application of the key idea of sustainable development in construction phase, which plays a significant role in promoting sustainable development of construction industry. Currently, tremendous energy and resources, particularly high-carbon materials, are consumed in construction activities in large-scale public projects. This poses a potential threat to the environment. However, carbon emissions related factors have not been considered in the bid evaluation of mega public projects. This study innovatively integrated CO_2 emission into the bid evaluation indicator system. The carbon emission indicators were identified through the analysis of carbon sources of all stages of construction. Then a uniform linguistic group decision-making framework for bid evaluation considering CO_2 emissions reduction was established. Entropy, relative entropy, the standard deviation method and weighted aggregation operators were applied to determine the indicator weights, the expert weights and the information aggregation in bid evaluation process. Finally, bid evaluations considering and without considering CO_2 emissions reduction were compared through a case study. The scenario comparison result indicated that the contractor with higher performance in CO_2 emissions reduction was superior to other contractors with less performance in CO_2 emissions reduction. The result also showed that considering CO_2 emissions reduction in bid evaluation was a scientific and reliable method in contractor selection.

The theoretical significance of establishing linguistic group decision-making framework considering CO_2 emissions reduction is that it can enrich the decision-making models and bid evaluation methods in the construction management field. The practical implication are as follows. To the owners and contractor units, this framework can not only provide meaningful support and guideline for owners to choose qualified contractors from an environmental viewpoint, i.e. with competent construction techniques or management skills etc., it can also spur contractors to improve their construction schemes, enabling the construction phase to be green, energy saving and sustainable, and a more efficient utilization of resources will therefore be ensured. In terms of the contribution to the construction industry and the society, it plays a significant role to establish the framework for the healthy development of construction industry in the whole society. Firstly, this framework can promote the construction industry to optimize and develop in a technology-intensive and low energy consumption direction. Secondly, green construction which was promoted by this bid evaluation framework can mitigate the environment pollution and ecological damage caused by traditional construction in the life cycle. Therefore the social benefit can be improved. Then the framework can provide a reference for establishing a sustainable development of the low-carbon construction management system, further to clarify the green building construction management specification. Apart from that, the establishment of this bid evaluation framework also provides a new idea for other project management evaluation, and it is conducive to the promotion of green construction management in the whole society.

The shortcoming and future research of this study is presented as in the follows. It is difficult to add all of the CO_2 emission from the materials or the equipment used in the construction, which is also the challenge of this study. Another limitation is that the specific amount of CO_2 emissions was not calculated; instead, these indicators were merely assessed by experts with linguistic variables. In a future study, (1) the quantity of CO_2 emissions in the construction phase and other phases during the life cycle period will be investigated and quantified for base on computer. This issue requires a prompt solution in construction and is also the foundation of a more objective and comprehensive bid evaluation. (2) We will conduct research to establish a carbon emissions trading scheme in the construction sector.

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