Perspective Discrepancy between Designers and Constructors on the Sustainability of Steel Structures: Are They Synthesizable?

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Abstract: City growth and its resulted environmental issues are promoting a citywide application of sustainable steel structures. However, designers and constructors often hold conflicting perspectives on the sustainable construction of steel structures, which has been identified as a barrier to achieve sustainability in this area. Given that the existing sustainability indicator systems of steel structures are either design-oriented or construction-driven, this study aims to develop a new one by synthesizing both designers' and contractors' opinions in the development of such indicators. Semi-structured interviews were conducted to identify potential indicators. A questionnaire survey was then used to collect the viewpoints of designers and constructors on the identified indicators. Finally, a fuzzy set algorithm and hierarchical clustering were employed to detect the indicators' relationships. The results present a three-dimensional indicator system composed of social-technical sustainability, greenness, and economic sustainability. Furthermore, it is found that designers and constructors have discrepant opinions on social-technical sustainability and greenness, while their views on economic sustainability are similar. The research findings provide managerial hints to the attainment of sustainable steel structures and enhance stakeholders' understanding of design-and-construction integration in steel structure projects.

Keywords: steel structures; sustainable construction; synthesizability; construction management; discrepancy

1. Introduction

Ongoing rapid urbanization has posed various challenges to the delivery of construction projects. One of the challenges is selecting and using green materials in the construction process. In a general sense, the use of construction materials can lead to diverse environment issues, such as dust pollution, gas emissions, and solid wastes [1]. To deal with these environmental issues and promote sustainable construction, it is of great importance to select and use environmentally-friendly construction materials.

Steel is a typical construction material with the advantages of recyclability, high strength, resource efficiency, and durability [2]. As reported by American institute of Steel Construction, around 98% of the materials used in a steel structure can be recycled at the end of a building’s life and the dry connection of steel structures also means less resource consumption (e.g., water). There can be found an increased popularity of developing steel structure buildings in practice. According to the Ministry of Housing and Urban-Rural Development of China, the market size of prefabricated steel structures in China is expected to rise from 800 billion Yuan to 2 trillion Yuan during 2020–2025. However, recent years have also witnessed unsustainability problems associated with steel construction, which is mainly resulted from the isolation of designers and constructors in construction process. Specifically, designers are obligated to satisfy clients’ sustainability requirements (e.g.,
building orientation, internal layout, landscape) in the design phase, and they might be unacquainted with the subsequent construction process [3]. On the contrary, constructors focus more on the construction activities, and they fulfill their construction duties in a way different from that of designers. Consequently, designers and constructors tend to have different perspectives on attaining sustainable steel structures [4].

The importance of both design and construction has been implied in the mainstream and leading sustainability assessment systems, such as the Leadership in Energy and Environmental Design (LEED) in the U.S. and the Environmental Assessment Method (BREEAM) in the U.K. For instance, LEED places importance on construction-related indicators such as “construction water efficiency” and “construction electricity consumption”. BREEAM stresses the design-related indicators, including “sustainable building site selection.” Due to the different focuses, the existing sustainability assessment systems cannot integrate both designers and constructors’ concerns in the development of sustainable steel structure projects. No effective approaches are available to develop a set of steel structure sustainability indicators that reflect the integrated requirements of design-construction.

The study aims to address this research gap by synthesizing perspectives of both designers and constructors on the sustainability of steel structures.

2. Literature Review

2.1. Sustainable Steel Structures

The construction industry is responsible for providing adequate built facilities to satisfy societal demands [5]. To address construction-related environmental impacts, it is essential to improve the environmental performance of construction activities through using green materials [6]. A large amount of steel materials is used in construction projects. With the fast development of urbanization, the demand for steel structure buildings will be even more. There are two main reasons leading to this phenomenon. First, the increasing urban population leads to the growing demand for housing and infrastructure. Therefore, new buildings and infrastructure projects are constantly being built, which leads to the gradual destruction of the urban environment. Second, the economic development of the world promotes the public to pursue a higher quality of life and a more comfortable living environment. The use of steel structures brings various environmental benefits such as reducing resource consumption, utilizing recyclable resources, and reducing toxic substances [7], which helps to meet the needs of sustainable urban development and provide a better living environment for human beings. Nevertheless, the application of steel structures is subject to much controversy on its ecological disturbance in the production stage, high maintenance cost [8], and easy corrosion [9].

Sustainable construction is a strategy used for addressing the environmental issues associated with the construction process. It helps construction stakeholders to reduce resource consumption, save life cycle cost, and improve safety and quality. The concept of “sustainable steel structures” is built on the triple bottom line of sustainability, and is also a proxy for meeting the environmental, economic, and social sustainability requirements of steel structures. In light of the concept of sustainable development, sustainable steel structures shall be defined as the built physical structures that are environmentally responsible and resource-efficient in their life-cycles. This definition comprises three dimensions, including environmental sustainability, economic sustainability, and social sustainability [9]. The environmental sustainability dimension embraces a closed material recycling loop to guarantee environmental performance. Regarding economic sustainability, sustainable steel structures should be economically sustainable through recycling and reusing steel materials. Moreover, steel structures in the social sustainability dimension are concerned with life quality improvement of occupiers.

2.2. Sustainability Indicators for Steel Structures

The negative impacts of steel structures on the physical environment have drawn much attention in the research community, and have promoted the development of sus-
tainability indicator systems. The sustainability assessment of buildings contributes to formulating an initial set of sustainability indicators for steel structures. Some leading databases, including Web of Science, and Google Scholar, were searched in the study. The used keywords in searching included “steel structure”, “engineering structure”, “steel building”, “steel sustainability” and “building sustainability”. Besides, several green building specifications were reviewed, including the Australian steel structure standards, China’s steel structure design standards, British structure use of steelwork in building, LEED, and BREEAM. Consequently, a list of sustainability indicators was formulated (Table 1), which is further categorized into three dimensions, namely social-technical sustainability, economic sustainability, and greenness, as discussed below.

Table 1. Sustainability indicators for steel structures.

| Indicator                                                                 | Source |
|--------------------------------------------------------------------------|--------|
| Functional Variability                                                   | [10]   |
| Matching between Structure and Architectural Function                    | [10]   |
| Reliability of Construction Plan                                         | [10]   |
| Maintenance Cost                                                         | [10]   |
| Construction Air Pollution                                               | [10]   |
| Carbon Emission                                                          | [10]   |
| Construction Solid Waste                                                 | [10,11]|
| Cyclic Utilization Rate of Structural Demolition                         | [10,11]|
| Water Consumption for Construction                                       | [10,11]|
| Bearing Capacity of Structure                                            | [12]   |
| Structural Adaptability                                                  | [12]   |
| Pre-Consulting Fee                                                       | [12]   |
| Design Fee                                                               | [12]   |
| Transportation Cost of Steel and Components                              | [12]   |
| Inter-Story Displacement Angle                                           | [12]   |
| Dismantling Cost                                                         | [12]   |
| Procurement of Materials                                                 | [12]   |
| Shape Coefficient of Building                                            | [13]   |
| Energy Consumption Capacity of Structure                                 | [13]   |
| Earthquake Fortification Intensity                                       | [14]   |
| Lateral Displacement Stiffness of Structure                              | [14]   |
| Deformation of Structural Members                                        | [14]   |
| Deformation of Non-Structural Components                                 | [14]   |
| Stress Relaxation of Components                                          | [14]   |
| Fatigue Strength of Components                                           | [14]   |
| Ultimate Strength of Steel                                               | [14]   |
| Ductility of Steel                                                       | [14]   |
| Fire Resistance and Weatherability of Steels                             | [14]   |
| Coefficient for Importance of Structure                                  | [15]   |
| Vulnerability of Structure                                               | [16]   |
| Structural Self-Reposition                                               | [16]   |
| Natural Period of Vibration of Structure                                 | [17]   |
| Structural Disaster Resistance                                           | [17]   |
| Structural Constructability                                              | [18]   |
| Construction Waste Water                                                 | [18]   |
| Utilization of Renewable Energy                                          | [18]   |
| Construction Electricity Consumption                                     | [18]   |
| Thermodynamics of Enclosure Structure                                    | [18]   |
| Living Comfort of Steel Structure                                        | [18]   |
| Construction Accuracy                                                    | [19]   |
| Installation Cost                                                        | [20]   |
| Operation Cost                                                           | [21]   |
| Repair Cost                                                              | [21]   |
| Building Area                                                            | [22]   |
| Utilization Ratio of Underground Space                                   | [22]   |
| Construction Land Area                                                   | [22]   |
| Green Rate                                                               | [22]   |
| Utilization Rate of Water-Saving Appliances                              | [22]   |
| Construction Noise Pollution                                             | [22]   |
| Indoor and Outdoor Air Quality after Completion                          | [22]   |
| Site Selection Conditions (LEED, BREEAM, CASBEE)                         |        |

Social-technical sustainability describes the physical functions, social benefits of steel structures, and the interaction between people and technology on construction sites. Various steel structure standards are developed based on social-technical indicators such as safety, durability, and applicability [23]. The safety and durability of a steel structure pertain to structural stability and building reliability as pursued in the design phase [24], while the applicability is dependent on the sociality of steel structures. It seems that the social-technical dimension contains a variety of indicators such as inter-story displace-
ment angle, earthquake fortification intensity, the fatigue strength of components, the vulnerability of structure, structural self-reposition, structural disaster resistance, structural constructability, living comfort of steel structures, structural adaptability, and match-ability between buildings and social needs. Table 2 numbers the social-technical sustainability indicators, the following text will use the corresponding code to indicate each indicator.

| Indicator Code | Indicator | Indicator Code | Indicator | Indicator Code |
|----------------|-----------|----------------|-----------|----------------|
| x1             | Shape Coefficient of Building | x10          | Stress Relaxation of Components | x19         |
| x2             | Earthquake Fortification Intensity | x11          | Fatigue Strength of Components | x20         |
| x3             | Coefficient for Importance of Structure | x12          | Ultimate Strength of Steel | x21         |
| x4             | Bearing Capacity of Structure | x13          | Steel Yield Strength | x22         |
| x5             | Energy Consumption Capacity of Structure | x14          | Ductility of Steel | x23         |
| x6             | Vulnerability of Structure | x15          | Fire Resistance and Weatherability of Steels | x24         |
| x7             | Structural Self-Reposition | x16          | Construction Accuracy | x25         |
| x8             | Natural Period of Vibration of Structure | x17          | Reliability of Construction Plan | x26         |
| x9             | Lateral Displacement Stiffness of Structure | x27          | Pre-Consulting Fee | x37         |
| x10            | Inter-Story Displacement Angle | x28          | Design Fee | x38         |
| x11            | Structural Disaster Resistance | x29          | Procurement of Materials | x39         |
| x12            | Structural Constructability | x30          | Transportation Cost of Steel and Components | x40         |
| x13            | Functional Variability | x31          | Operation Cost | x41         |
| x14            | Structural Adaptability | x32          | Maintenance Cost | x42         |
| x15            | Living Comfort of Steel Structure | x33          | Repair Cost | x43         |
| x16            | Matching between Structure and Architectural Function | x34          | Dismantling Cost | x44         |
| x17            | Reliability of Construction Plan | x35          | Installation Cost | x45         |

The economic indicators comprise pre-consulting fees, design fees, and the costs of procurement, construction, maintenance, and operation. In reality, the transportation and installation of steel materials occupy a significant proportion of the life-cycle cost of a steel structure project. Steel structures are known for their long-lasting, high recyclability, and flexible reusability, which indicates that the economic sustainability of steel structures can be actualized through the effective use of steel materials. Table 3 shows the economic indicators and their code.

| Indicator Code | Indicator | Indicator Code | Indicator |
|----------------|-----------|----------------|-----------|
| x27 | Pre-Consulting Fee | x30 | Repair Cost |
| x28 | Design Fee | x31 | Dismantling Cost |
| x29 | Procurement of Materials | x32 | Installation Cost |

The greenness indicators are multifaceted. As LEED specifies, the indicators are green sites, water efficiency, energy and atmosphere, materials, and resource. These indicators are widely accepted in the construction context. For instance, CASBEE (2004) highlights energy consumption, resource reuse, local environment, and air quality. The thermodynamics of enclosure structure, construction solid waste, and construction wastewater were proposed by Jin and Niu [25]. In summary, steel structures remain one of the most environmentally sensitive construction materials. The greenness of steel structures should react to an increased concern about resource consumption, construction waste, environmental degradation, and climate change in the construction industry [26]. Table 4 is the greenness indicators and its code.

2.3. Synthesizing the Perspectives of Designers and Contractors in Sustainability Attainment

In appreciating the complexity of steel structures, designers and constructors are increasingly aware of the need to invest in sustainable practices. To this end, designers’ intention should be realized by constructors, while the constructability issues of steel structures should be evaluated in the design phase [27]. The design stage is dominated by designers who provide design solutions (e.g., building size, function, landscape, and facilities) based on the clients’ sustainability requirements [28,29]. Meanwhile, constructors take the responsibility of satisfying clients’ sustainability requirements at the construction phase, such as reducing carbon emissions, decreasing wastewater discharge, improving constructability, and ensuring timely delivery [30].
In traditional procurement systems, clients enter into contracts with designers and constructors separately. Such a project delivery mode leads to potential conflicts between these two entities due to their different perspectives in serving clients. Empirical studies have shown that the lack of effective interactions and poor teamwork between designers and constructors cause unsustainable problems (e.g., rework, low quality, change orders, schedule delay, and cost overrun) [31,32]. To resolve such issues, Assaf [33] suggested that constructors should be involved into the design phase and designers should also extend their services forwards to the construction stage. Thus, the sustainability of steel structures will be attained by keeping both designers and constructors working consistently.

On many occasions, construction plans, and detailed drawing schemes are mistakenly followed after the design phase [34]. The involvement of constructors in the design stage helps to improve the design quality by integrating the expertise of contractors in design solutions. Especially, the proactive participation of constructors in the design phase facilitates designers to understand technical changes and constructability issues, which helps to save cost and avoid resource wastes [35]. It seems that the synthesis of designers and constructors contributes to the sustainability performance improvement of steel structures. Consequently, the high cost of design changes, poor quality of building structure, and building materials waste will be inhibited [36].

### 3. Methodology

In the study, interviews were conducted to supplement the preliminary indicators listed in Table 1. In addition, a questionnaire survey was used to collect the importance of the indicators. Moreover, a fuzzy set algorithm was adopted to select sustainability indicators for steel structures, and hierarchical clustering was also used to examine the relationships of indicators.

#### 3.1. Identifying the Indicators

The semi-structured interview was used to collect interviewees’ opinions on a particular subject [37]. During 12–15 May 2019, five experts with rich knowledge and experience in steel structures were interviewed to judge the effectiveness of the preliminary indicators. Among these five experts, two of them are working in well-known design institutes in China. Another two are from top Chinese steel structure professional enterprises, and the remaining one is a professor working at a top university in China. As Table 5 shows, all these interviewees have over ten years of work experience in the steel construction sector.

### Table 5. Profiles of the interviewees.

| Respondent | Position                  | Type              | Years of Work |
|------------|---------------------------|-------------------|---------------|
| A          | Chief Engineer            | Design Institute  | 16            |
| B          | Senior Engineer           | Design Institute  | 11            |
| C          | Deputy Chief Engineer     | Construction      | 21            |
| D          | Chief Engineer            | Construction      | 23            |
| E          | Full Professor            | Academic          | 11            |

Note: details about the interviewees are omitted for privacy.
The open interview questions were designed to solicit experts’ opinions on preliminary indicators of sustainable steel structure. These questions include: (1) Concerning the sustainability of steel structures, what aspects do you think designers and constructors emphasize, respectively? (2) Is it reasonable to divide the sustainability indicators into greenness, structural performance, and greenness? (3) How about the effectiveness of the indicators? The interviewees were also requested to evaluate the indicators carefully and to modify the indicators if necessary. Each interview lasted for around two hours. The interviews were conducted in three major cities of China, including Chengdu, Shenzhen, and Chongqing. The interviews were audio recorded, and the recordings were transcribed in written scripts in Chinese. The scripts were also returned to the interviewees for verification.

The results of these interviews are four-faceted. First, those indicators with similar meanings (e.g., land use scheme, land master plan) were unified. Second, three indicators in the operation stage (e.g., component replaceability) were complemented because clients are sensitive to the applicability and maintainability of steel structures in the operation phase. Third, four indicators (e.g., the corrosion rate of steel and welding residual stress) were also included to reflect the features of steel materials. Another four indicators, including natural lighting coefficient and construction light pollution, were proposed from a life cycle perspective. Fourth, three additional indicators (e.g., design working life of a structure, structural demolition cycle) were included. At last, the experts suggested the classification of the preliminary indicators into three groups, including social-technical sustainability, economic sustainability, and greenness. Consequently, twenty-two sustainability indicators were identified (Table 6).

### Table 6. Sustainability indicators for steel structures.

| Indicator                              | Code | Indicator                          | Code |
|----------------------------------------|------|------------------------------------|------|
| FloorAreRatio                          | x54  | Investment Amount                  | x66  |
| Design Working Life of Structure       | x55  | Steel Consumption Per Square Meter | x67  |
| Maintenance Convenience of Structure and Material | x56  | Cost of Component Manufacturing and Processing | x68  |
| Construction Period of Structure       | x57  | Waste Disposal Cost                | x69  |
| Durability of Structure                | x58  | Monitoring Cost of Steel Structure  | x70  |
| Structural Demolition Cycle            | x59  | Residual Value of Steel Structure   | x71  |
| Stiffness Degradation Rate of Components | x60   | Natural Lighting Coefficient       | x72  |
| Component Replaceability               | x61  | Construction Light Pollution        | x73  |
| Welding Residual Stress                | x62  | Light Environmental Parameters Reaching Standard Rate after Completion | x74  |
| Weldability of Steel                   | x63  | Acoustic Environmental Parameters Reaching Standard Rate after Completion | x75  |
| Corrosion Rate of Steel                | x64  |                                   |      |
| Matching Between Enclosure Structure and Steel Structure | x65  |                                   |      |

#### 3.2. Questionnaire Survey

The questionnaire survey was used to gather respondents’ views on the importance of the indicators. The questionnaire contains three sections, including profiles of participants (e.g., education background, years of work), expertise of participants in steel structures, and indicators importance. The five-point Likert scale was employed to judge the importance level of the indicators, where “5” means extremely important, “4” means important, “3” means average, “2” means unimportant, and “1” means extremely unimportant, respectively.

The respondents of this study were selected based on their professions, knowledge, and experience in the steel structure field. A questionnaire was sent out to targeted respondents by using the snowball sampling technique. The survey started from the China Southwest Architectural Design and Research Institute and China Steel Structure Construction Corporation. Both of two are leading companies in the Chinese construction industry. With these two companies’ assistance, professionals from other top-tier construction firms...
in China were invited to participate in the survey. The survey was implemented during June–July 2019. In total, one hundred and ten completed questionnaires were returned. A total of 18.63% of the respondents have over 20-years working experience in the construction industry. Further, 41.6%, 33.37%, and 6.4% of these participants have 11–20 years, 3–10 years, and less than 3 years working experience in the construction industry, respectively. However, four of the returned questionnaires were invalid and excluded given that their respondents were not professionals in steel structures. Another seven questionnaires were also excluded due to their respondents’ insufficient experience (less than two years). Therefore, 99 questionnaires were retained for analysis, including 45 constructors and 54 designers. These respondents were from diverse provinces of China, including Beijing, Shanghai, Guangdong, Jiangsu, Chongqing, Fujian, Zhejiang, Anhui, and Guizhou.

3.3. Data Analysis

The reliability and validity of data present the adequacy of research results. If variables are classified, it is essential to examine the reliability of data classification. In the study, the sustainability indicators were categorized into different groups, and the Cronbach’s alpha was used to reflect the reliability of the classification. The classification was reliable as the Cronbach’s alpha of this study is larger than 0.7 [38].

3.3.1. A Fuzzy Set Algorithm

First, the data obtained from the questionnaire survey has the characteristics of subjectivity. The fuzzy set theory is suitable for dealing with such type of data. In addition, the fuzzy set algorithm can effectively integrate the opinions of different subjects, which has been confirmed in previous similar studies [39]. Therefore, fuzzy set theory was adopted to integrate the opinions of designers and constructors in order to establish a comprehensive indicator system. The use of this method includes four steps. First, a fuzzy set was defined to determine the distribution of membership functions. Second, the memberships were calculated for the designer group and the constructor group, respectively. Third, the union operator serves to calculate the comprehensive membership per indicator. At last, the indicator set was determined by referring to the resulted comprehensive memberships. The symbol $\mathbf{A}$ is employed to represent a set of sustainability indicators of steel structures. This set is defined as a fuzzy set $\mathbf{A}_D$ and $\mathbf{A}_C$, which represents the assessment indicator set of designers and constructors, respectively.

\[
\mathbf{A} = \frac{\mu_\mathbf{A}(x_0)}{x_0} + \frac{\mu_\mathbf{A}(x_1)}{x_1} + \ldots = \sum_{i=0}^{n} \frac{\mu_\mathbf{A}(x_i)}{x_i}
\]

where $x_i$ is the ith indicator; $n$ is the number of indicators; $\mu_\mathbf{A}(x_i)$ is the membership of $x_i$ in the fuzzy set $\mathbf{A}$. Particularly in Equation (1), “+” and “/” are the symbols of the fuzzy set. $\mu_\mathbf{A}(x_i)/x_i$ means that the membership of $x_i$ in $\mathbf{A}$ is $\mu_\mathbf{A}(x_i)$.

The distribution of membership functions includes rectangular distribution, trapezoidal distribution, $K^{th}$ order parabola, normal distribution, and Cauchy distribution [40]. There are two types of statistical tests, including a parametric statistical test and a non-parametric statistical test [41]. The parametric method has the specific requirement that the data to be analyzed must fall in a normal distribution. In contrast, the non-parametric approach does not need such a particular distribution [42]. In the study, the W test’s non-parametric method was adopted to explore the survey results’ distribution. The W test’s null hypothesis is that the population is normally distributed if the $p$-value is higher than 0.05.

According to the fuzzy set theory, the probability that a variable belongs to a set is equal to the degree of membership in a fuzzy set [43]. Hence, Equation (2) is used to calculate memberships in two groups—designers and constructors.

\[
\mu_\mathbf{A}_{D,C}(x_i) = \int_{Q}^{\infty} f(S_{x_i})dx = 1 - P_f
\]
where $\mu_{AD(C)}(x_i)$ indicates that the membership of indicator $x_i$ in the fuzzy set $\overline{A}_D$ or $\overline{A}_C$; $f(S_{x_i})$ is a membership function, $P_f$ indicates the probability that the variable does not belong to the set.

The introduction of parameter $Z$ aims to calculate the value of $P_f$ when $f(S_{x_i})$ is normally distributed. Equation (3) is used to calculate the $Z$ value.

$$Z = (M - Q)/SD$$ (3)

where $M$ and S.D. represent the average score and standard deviation of an indicator. $Q$ is equal to 3 in line with the definition of the five-point Likert Scale.

The comprehensive membership is defined by using Equation (4) [44] and calculated by using Equation (5). The larger the value, the more important the indicator.

$$\overline{A} = \overline{A}_D \cup \overline{A}_C \cup \ldots = \{x, \mu_{\overline{A}_D \cup \overline{A}_C \cup \ldots}(x)|x \in X\}$$ (4)

$$\mu_{\overline{A}_D \cup \overline{A}_C \cup \ldots}(x) = \min\left\{1, \left[\mu_{\overline{A}_D}(x)^n + \mu_{\overline{A}_C}(x)^n + \ldots\right]^{1/n}\right\}, \quad n \geq 1$$ (5)

where $n$ is the total number of indicators. The $\lambda$-cut set approach, which transfers a fuzzy set to a classical set, was adopted to identify the sustainability indicators. As suggested by Tervonen et al. [45], the rule of thumb is that the $\lambda$ value should fall into the interval between 0.65 and 0.85.

### 3.3.2. Hierarchical Clustering

Hierarchical clustering is a method of dividing different objects into groups based on cluster distances, and objects with similar features are classified into one same group [46]. Given that the respondents were from two different types of businesses and many indicators involved, the hierarchical clustering was considered as sufficient to compare designers and constructors’ opinions on the importance of indicators. In this study, the cluster distance between pairs of indicators was quantified based on the Euclidean distance.

$$ED(x_i, x_{i+1}) = \sqrt{[M(D_{x_i}) - M(D_{x_{i+1}})]^2 + [M(C_{x_i}) - M(C_{x_{i+1}})]^2}$$ (6)

where $ED(x_i, x_{i+1})$ indicates the distance between indicators $x_i$ and $x_{i+1}$. $M(D_{x_i})$ and $M(C_{x_i})$ represent the average value of indicators scored by designers and constructors, respectively.

The steps of operating Equation (6) are as follows.

1. Calculating the optimal number of clusters so that these groups are compact and well-separated.
2. Calculating the average score for indicator $x_i$.
3. Based on $M(D_{x_i})$ and $M(C_{x_i})$, the indicator pair with the smallest distance was grouped. This process was repeated until the optimal number of clusters was derived.

### 4. Results

#### 4.1. A Preliminary Indicator Set

Table 7 shows the preliminary indicators and their classification based on the literature review and interviews. The interviewees advised that the sustainability indicators of steel structures can be categorized into three dimensions, including social-technical sustainability, economic sustainability, and greenness. The Cronbach’s alpha coefficients of social-technical sustainability, economic sustainability, and greenness are 0.95, 0.93, and 0.956, respectively, which means that the questionnaire data are reliable (larger than 0.7).

Table 8 shows the average values and standard deviations of the preliminary indicators. It is noted that the two groups have different results regarding the mean and variance values. Taking the indicator $x_{12}$ as an example, the average score of designers is 3.981 (16th), whereas the constructors’ average score is 4.378 (5th). Besides, the W test results for the
conductor and designer groups are larger than 5%, which suggests that the membership function can be deemed to be normally distributed.

Table 7. A preliminary indicator set of steel structures.

| Social-Technical Sustainability | Economic Sustainability | Greenness |
|--------------------------------|-------------------------|-----------|
|                                |                         |           |
| X1                              |                         |           |
|                                |                         |           |
| X6                              |                         |           |
|                                |                         |           |
| X11                             |                         |           |
|                                |                         |           |
| X16                             |                         |           |
|                                |                         |           |
| X21                             |                         |           |
|                                |                         |           |
| X26                             |                         |           |
|                                |                         |           |
| X58                             |                         |           |
|                                |                         |           |
| X63                             |                         |           |

Table 8. Mean and variance of the preliminary indicators.

| Code | M(C) | SD | M(D) | SD | Code | M(C) | SD | M(D) | SD |
|------|------|----|------|----|------|------|----|------|----|
| x1   | 3.778 | 0.927 | 3.241 | 1.148 | x26 | 4.133 | 0.588 | 3.852 | 1.053 |
| x2   | 4.467 | 0.661 | 4.167 | 1.023 | x27 | 3.511 | 0.869 | 3.574 | 1.075 |
| x3   | 3.311 | 0.596 | 3.796 | 1.122 | x28 | 3.667 | 0.853 | 3.759 | 1.098 |
| x4   | 4.444 | 0.586 | 4.370 | 0.917 | x29 | 4.200 | 0.727 | 4.185 | 1.150 |
| x5   | 4.022 | 0.839 | 4.019 | 1.205 | x30 | 3.933 | 0.809 | 3.815 | 1.100 |
| x6   | 4.000 | 0.769 | 3.981 | 1.090 | x31 | 3.600 | 0.837 | 3.704 | 1.110 |
| x7   | 4.089 | 0.668 | 3.778 | 1.040 | x32 | 3.711 | 0.895 | 3.945 | 1.054 |
| x8   | 4.022 | 0.783 | 3.407 | 1.125 | x33 | 3.711 | 0.843 | 3.741 | 1.119 |
| x9   | 3.978 | 0.753 | 3.593 | 1.141 | x34 | 3.222 | 0.997 | 3.222 | 1.093 |
| x10  | 3.978 | 0.723 | 3.574 | 1.207 | x35 | 4.000 | 0.769 | 3.963 | 1.063 |
| x11  | 4.511 | 0.626 | 4.259 | 1.031 | x36 | 3.733 | 1.031 | 3.444 | 1.284 |
| x12  | 4.378 | 0.614 | 3.981 | 1.107 | x37 | 3.733 | 1.053 | 3.630 | 1.233 |
| x13  | 3.800 | 0.919 | 3.537 | 1.077 | x38 | 3.578 | 1.076 | 2.759 | 1.273 |
| x14  | 3.911 | 0.793 | 3.685 | 1.006 | x39 | 3.778 | 1.020 | 3.093 | 1.248 |
| x15  | 3.800 | 0.726 | 3.815 | 1.083 | x40 | 3.689 | 0.925 | 2.815 | 1.199 |
| x16  | 4.044 | 0.706 | 3.870 | 1.047 | x41 | 3.889 | 0.859 | 3.926 | 1.096 |
| x17  | 4.087 | 0.688 | 3.685 | 1.079 | x42 | 3.978 | 0.866 | 3.944 | 1.089 |
| x18  | 3.556 | 0.918 | 3.204 | 1.122 | x43 | 3.800 | 0.786 | 3.167 | 1.255 |
| x19  | 3.903 | 0.688 | 3.741 | 1.013 | x44 | 3.511 | 1.121 | 3.074 | 1.195 |
| x20  | 4.178 | 0.650 | 3.667 | 1.046 | x45 | 3.756 | 1.048 | 3.611 | 1.071 |
| x21  | 4.200 | 0.694 | 4.130 | 0.953 | x46 | 3.467 | 1.100 | 2.815 | 1.100 |
| x22  | 4.267 | 0.688 | 4.111 | 0.965 | x47 | 3.356 | 1.151 | 2.852 | 1.188 |
| x23  | 4.133 | 0.694 | 4.037 | 1.115 | x48 | 3.533 | 1.100 | 3.330 | 1.214 |
| x24  | 4.311 | 0.733 | 4.093 | 1.137 | x49 | 3.600 | 0.986 | 3.389 | 1.188 |
| x25  | 4.156 | 0.706 | 3.852 | 0.998 | x50 | 3.667 | 1.000 | 3.556 | 1.160 |

Note: M(D) means the average value marked by designers; M(C) represents the average value given by constructors.

4.2. Comprehensive Membership

Based on the mean and variance of the preliminary indicators (Table 8) and Equations (2) and (3), the parameter Z and the membership per indicator in $\overline{A}_D$ and $\overline{A}_C$ were calculated. The results demonstrate that the membership of social-technical indicators is 0.303–0.932 and 0.601–0.993, respectively, and the membership of economic sustainability indicators $\overline{A}_C$ is 0.581–0.972 and 0.588–0.992, respectively. Regarding the greenness indicators, the results are 0.423–0.807 and 0.621–0.871, respectively. The scatter distribution of the membership value of “designer-constructor” is shown in Figure 1.

As shown in Figure 1, some indicators are located at the top right areas, which indicates a larger membership. On the contrary, those indicators located at the bottom left have a smaller value. This distribution shows that designers and constructors have a consistent perception of the indicators. Besides, some of the indicators are located at the top left and bottom right of the figure. The discrete distribution is representative of the different perceptions between designers and constructors. Each point shows the extent to which designers and constructors have different attitudes towards a given indicator. For instance, the membership of indicator x34 for constructors is 0.601, whereas its value for
designers is 0.303. This finding suggests that the indicator \( x_{54} \) attracts more attention from constructors than that from designers.

The comprehensive membership per indicator is calculated by using Equations (4) and (5) \( (t = 75) \). \( \lambda \) equals 0.75, which means that when the membership is less than 0.75, the indicator deserves exclusion. Consequently, the indicators for the sustainability of steel structures and their comprehensive memberships are derived, which is shown in Table 9.

The indicators in Table 9 are classified into different dimensions, including social-technical sustainability \((0.915)\), economic sustainability \((0.804)\), and greenness \((0.746)\). The social-technical sustainability dimension has the largest membership, which is ranked as the most important dimension. The “bearing capacity of the structure”, “investment amount”, and “utilization of renewable energy” are the most important indicators in the relevant dimensions, with their membership values being 0.993, 0.994, and 0.871, respectively. clearpage

![Figure 1. Scatter distribution of “designers-constructors” membership. Note: \( \mu_C \) and \( \mu_D \) represents the membership values of the indicators in \( \mathcal{A}_C \) and \( \mathcal{A}_D \), respectively.](image)

| Indicator \( x_i \) | Social-Technical Sustainability \((Mean = 0.915)\) | Economic Sustainability \((Mean = 0.804)\) | Greenness \((Mean = 0.746)\) |
|---------------------|---------------------------------|---------------------------------|---------------------------------|
| \( x_1 \) 0.799 | 48 | \( x_{17} \) 0.808 | 46 | \( x_{36} \) 0.973 | 9 | \( x_{28} \) 0.784 | 41 | \( x_{46} \) 0.761 | 54 |
| \( x_2 \) 0.987 | 7 | \( x_{14} \) 0.875 | 32 | \( x_{45} \) 0.951 | 16 | \( x_{29} \) 0.944 | 21 | \( x_{37} \) 0.757 | 56 |
| \( x_3 \) 0.986 | 8 | \( x_{15} \) 0.865 | 40 | \( x_{36} \) 0.918 | 28 | \( x_{30} \) 0.876 | 37 | \( x_{39} \) 0.777 | 50 |
| \( x_4 \) 0.993 | 2 | \( x_{16} \) 0.931 | 24 | \( x_{13} \) 0.958 | 15 | \( x_{31} \) 0.764 | 53 | \( x_{40} \) 0.772 | 51 |
| \( x_8 \) 0.888 | 35 | \( x_{17} \) 0.940 | 23 | \( x_{28} \) 0.942 | 22 | \( x_{32} \) 0.816 | 45 | \( x_{41} \) 0.850 | 41 |
| \( x_9 \) 0.903 | 33 | \( x_{19} \) 0.913 | 29 | \( x_{39} \) 0.753 | 57 | \( x_{33} \) 0.801 | 47 | \( x_{42} \) 0.871 | 39 |
| \( x_7 \) 0.948 | 20 | \( x_{20} \) 0.965 | 11 | \( x_{40} \) 0.922 | 26 | \( x_{35} \) 0.903 | 32 | \( x_{43} \) 0.846 | 42 |
| \( x_5 \) 0.904 | 31 | \( x_{21} \) 0.998 | 14 | \( x_{31} \) 0.883 | 35 | \( x_{46} \) 0.994 | 1 | \( x_{45} \) 0.765 | 52 |
| \( x_6 \) 0.903 | 34 | \( x_{22} \) 0.967 | 10 | \( x_{42} \) 0.986 | 7 | \( x_{37} \) 0.961 | 13 | \( x_{52} \) 0.834 | 43 |
| \( x_{10} \) 0.912 | 30 | \( x_{23} \) 0.949 | 19 | \( x_{43} \) 0.992 | 4 | \( x_{48} \) 0.950 | 17 | \( x_{53} \) 0.821 | 44 |
| \( x_{11} \) 0.992 | 3 | \( x_{54} \) 0.963 | 12 | \( x_{44} \) 0.927 | 25 | \( x_{75} \) 0.761 | 55 |
4.3. Hierarchical Clustering

Figure 2 presents the results of the cumulative coefficients. As shown in the figure, when the abscissa is 5, the cumulative coefficient polyline’s downward trend turns to be slow. Hence, the optimal number of social-technical indicators is 5. The same process is operated again to derive the optimal number of the other two dimensions—economic sustainability and greenness.

Figure 2. Social-technical sustainability indicators line graph of the cumulative coefficient.

The social-technical sustainability indicators are hierarchically clustered by using Equation (6), and the result is shown as a two-dimensional scatter plot of “Ms(D)-Ms(C)” (Figure 3). It is shown that there are five clusters of social-technical sustainability indicators, and designers and constructors tend to hold different views on Clusters 2 (e.g., x17, x20), 3 (e.g., x8, x15), 4 (e.g., x3, x62), and 5 (x1).

The linear regression method is employed to test designers and constructors’ views on economic sustainability indicators. It was found that M(D) and M(C) satisfy the fitting function \( y = 0.871x + 0.544 \) (\( R^2 \) value is 0.822), which is shown in Figure 4 and suggests that designers and constructors have the same opinions about all of the economic sustainability indicators.

Figure 3. Clusters of social-technical sustainability indicators.
Figure 4. Clusters of economic sustainability indicators.

The indicators are clustered by using the Equation (6), and the two-dimensional scatter diagram of “Mg(C)-Mg(D)” is derived (Figure 5). Given that Clusters 1 and 2 are closely distributed, the linear curve can be cited to model the indicators’ relationships. The derived function is $y = 1.918x - 3.615$ ($R^2$ value is 0.857). Thus, the greenness indicators are comprised of three clusters, and it is found that designers and constructors have significantly different views on one cluster of the indicators (Cluster 3).

Figure 5. Clusters of greenness indicators.

5. Findings and Discussion

The derived 57 indicators constitute a wide-ranging indicator system for assessing the sustainability performance of steel structures. This new indicator system embraces all stages of a project life cycle and includes the three dimensions of social-technical sustainability, economic sustainability, and greenness [47,48]. Of these three dimensions, social-technical sustainability refers to the properties of building structures such as steel...
yield strength. The economic sustainability dimension spells out the cost-saving capability of a steel structure from a lifecycle perspective. The greenness dimension represents resource-saving, environmental protection, and pollution reduction to provide an environmentally responsible city environment. The derived three-dimensional indicator system is partly supported by Aghayere [49], which states that the better the technical functions of a building, the more the social sustainability (e.g., improved safety). However, compared with previous studies, the indicator system developed in the study exhibits new features of sustainable steel structures, as discussed below.

5.1. Synthesizability of the Two Perspectives

Synthesizability has been widely used in synthetic fiber and synthetic information systems [50]. It intends to combine separate parts to form a new system, and this new system will function better than its counterparts. In this study, designers and constructors play different roles in the development of steel structures. The synthesis of these two perspectives helps to develop a new sustainability indicator system that can be used to resolve conflicts and inconsistencies between design and construction. Traditionally, constructors have to compromise with designers’ initiatives if the used sustainability assessment indicators are design-oriented. Similarly, designers are forced to compromise with constructors’ needs if the indicator system is based on construction activities.

This new indicator system reflects the importance of synthesizing the divergent views of designers and constructors to attain sustainable steel structures. In practice, both design and construction are complex processes that contain many interlocked know-hows. Conflicts will occur given the poor coordination between designers and constructors in the design and construction process. As suggested by the newly developed indicator system, designers can better forecast potential construction-related issues before the construction phase and address constructors’ demands in project schematics. Meanwhile, constructors can detect the potential issues caused by design errors and react to these issues effectively.

5.2. Discrepancy of the Two Perspectives

Discrepancy means there are some conflicts or changes between facts, figures, or claims. It represents different types of opinions that are associated with different cognition. The results reveal that social-technical sustainability is characterized by indicator discrepancy. As listed in Table 9, the “bearing capacity of structure” is a primary indicator of social-technical sustainability. This indicator acknowledges the advantages of high carrying capacity of steel structures from the perspective of technical sustainability. It also underlines the value of structural safety for end-users, which may be considered a proxy for social sustainability. This finding is consistent with Ghavami et al.’s [51] views that structural bearing capacity is the basis of comfort for users. It also sheds new light on steel structures’ social-technical performance. In effect, this indicator’s dual role embodies the rationale of sustainable construction by giving a broader definition of social sustainability, namely social-technical sustainability.

The results indicate that designers and constructors are prone to bias towards some indicators, including “structural constructability” and “weldability of steel”. The reason is that constructors are accustomed to advanced technologies, construction plans, and construction operability in the construction process. However, designers might not be inclined to them due to the scope of services [52]. On the contrary, designers may purport to those indicators such as “vulnerability of structure” and “living comfort of steel structure” differently from what constructors do. Therefore, if designers fail to work on these indicators from design-construction integration, it will make inefficiency in the construction process and give rise to construction accidents.

The discrepancy of sustainability indicators also applies to the dimension of greenness. Figure 5 shows the differences between designers and constructors in evaluating the greenness indicators. Constructors hold that the “utilization ratio of underground space”, “construction land area” and “construction electricity consumption” are critical,
whereas designers insist that such indicators make no sense. This is partial, provided that construction engineers, who control this type of indicator, represent construction enterprises’ interests instead of design institutes. In this study, it is suggested that design enterprises should more consider such indicators in the project implementation process. As many countries have not enforced greenness specifications for steel structures, assessing environmental sustainability for steel structure projects might be challenging. A typical example is that Israeli attaches importance to the indicators of “evaluator impression” and “solid waste” in the building performance assessment system [53]. Jordan emphasizes the efficient use of environmental resources and deems the “soil protection” and “plant coverage” indicators to be crucial [54]. At a county level, it is understandable that the greenness indicators in China’s urbanization context differ from that in other counties such as Israel and Jordan.

5.3. Similarity of Economic Sustainability

Regarding the economic sustainability of steel structures, designers and constructors share similar opinions on its indicators. As shown in Table 9, construction cost, maintenance cost, operating cost, repair cost, dismantling cost, and waste disposal cost are included in the economic sustainability dimension. The cost of developing steel structure projects is higher than that of developing concrete structure projects, which draws both designers and constructors to carefully predict building investment. This study shows that the investment amount is crucial in determining whether a steel structure project is accepted by the developer [55]. It implies that the investment amount of the steel structures project will help the contractor successfully win the bid and help the developer abandon those projects that are not “value for money” in time.

The similarity of this dimension of indicators is also attributed to the transparency of a steel structure project’s cost in procuring the services of design, contracting, and maintenance. Most parts of steel structures are produced in factories and transported to construction sites for assembly and installation. This means that metal materials and maintenance occupy a more significant proportion of steel structures’ construction cost. Thus, the maintenance cost and operating cost are important indicators for managing investment amount better. This research finding provides contractors with more clear guidance about the development of the economic sustainability of steel structures. According to some historical studies [56], the cost issue is one of the most significant barriers to implementing off-site construction projects (e.g., steel structures). Therefore, while the findings concur with previous studies on the importance of construction cost of steel structures, the study modifies the existing economic sustainability indicators from a life cycle costing perspective.

5.4. Implications

The application results of the fuzzy set algorithm refer to 57 sustainability indicators that span widely over three dimensions, namely social-technical sustainability (36 indicators), economic sustainability (10 indicators), and greenness (11 indicators). These dimensions stress the importance of technical concerns in achieving sustainability and thus better match the uniqueness of steel structures. This implies that all social-technical, economic sustainability, and greenness elements are necessary to account for the scope of the sustainable steel structure. The improved three dimensions provide a theoretical basis for exploring the sustainability of different structural types. The research findings suggest that different types of building structures may exhibit inconsistent sustainability performance, and different management measures should be taken to achieve sustainability in practice.

The research findings imply that the divergent concerns between designers and constructors over the sustainability indicators are synthesizable by using a fuzzy set algorithm. The results also indicated that the sustainability assessment system for steel structures has shifted from a single view of design or construction to a synthesized one. While the fuzzy
set algorithm is advocated to use as an alternative approach to improve current sustain-
ability indicators, it is implied that the application of sustainable urbanization in this area
should account for the uniqueness of steel structure projects. For instance, by absorbing
designers and constructors’ opinions, the sustainability indicators of steel structures have
to consider a long product lifecycle and high steel structure performance.

A large scale of steel structure projects is being initiated, but the relevant unsustainable
accidents are enlarging in the meantime. Most of these accidents are due to designers and
constructors who stay in their positions to implement and assess the steel project's sustain-
ability. The synthesized sustainability indicators suggest that designers and construction
parties should cooperate and communicate in advance, and provide implications for prac-
titioners to integrate the views of both designers and constructors. The research findings
would be a useful reference for other countries to develop a steel structure assessment
system. Specifically, by using the indicator system, constructors can recognize unreason-
able schemes and unbuildable steel structure components at an earlier stage. Thereby,
reducing design changes, saving money and construction time, and using less materials
will be actualized. The sustainability indicators help designers to understand the main
concerns of constructors in the construction process, such as steel ductility, construction
accuracy, and structure reliability. Besides, the client may find it supportive for assessing
the potential performance of steel structures and gauging the design or construction phase
deficiencies. Therefore, the findings can help to identify the inconsistency of designers
and constructors in building steel structures and help to propose measures to alleviate
these inconsistent problems.

Furthermore, the above conclusions can be combined with information technologies
to realize the integration of design and construction in the management process. For
example, importing comprehensive indicators into the network information platform
reminds both parties to identify contradictions and deficiencies in advance, which will help
both parties to cooperate more efficiently. The platform can also transparently store and
analyze a large amount of project information and data, which helps to explore the internal
mechanism of the sustainable development of steel structure buildings. For example,
the relationship between different types of indicators can be discovered through data
analysis of the platform, which helps to realize the supervision and prediction of the cost,
construction period, and quality of steel structure projects.

6. Conclusions

The disintegration of design and construction in the construction process makes it
difficult for designers and constructors to reach a broad consensus on the sustainability
indicators. This has been an outstanding issue in the construction of sustainable steel
structures. Given that designers and constructors have different perceptions of sustainable
steel structures, the use of the fuzzy set theory model in this study is suitable to synthesize
the different views of these two entities.

The following conclusions were drawn in this study: (1) The derived sustainability in-
dicator system which is comprised of social-technical sustainability, economic sustainability,
and greenness can not only fully and effectively reflects the performance dimensions of steel
structure but also provides a new roadmap to integrate design and construction. (2) There
is a discrepancy correlation between designers and constructors in the social-technical sus-
tainability and greenness dimension. The social-technical indicators are divided into five
categories, and the views of designers and constructors on each category are not completely
consistent. Designers and constructors have a discrepancy opinion for the utilization ratio
of underground space, construction land area, and construction electricity consumption in
the greenness dimension. (3) There is a correlation between designers and constructors
in the economic sustainability dimension. Meanwhile, the results indicate that the top
three indicators are procurement of material, investment amount, steel consumption per
square meter, with the investment amount having potentially the largest impact. These
similarity indicators represent the cooperation content that the designers and contractors
have approved. However, the discrepancy indicators require designers and contractors to pay more attention in practice.

This research enriches and extends the existing sustainability indicator systems for steel structures by synthesizing the opinions of designers and contractors. This represents an advancement compared with historical studies that mainly explored sustainability indicators from the perspective of either designers or contractors. Further, a new approach was designed in this study to integrate the views of different professionals. Besides, the developed sustainability indicator system facilitates the sustainability performance assessment of steel structures, which supports the sustainable development of the steel structure sector. In practice, governments can better guide the application of steel structures by addressing the identified sustainability indicators in their policies. Design institutes and construction companies can better manage steel structure projects from a more comprehensive perspective to avoid the unsustainable phenomena. For instance, before the designer starts work, this set of indicators can be adopted to remind the designer to consider the construction parameters so as to ensure that the construction plan can be implemented smoothly during the construction phase. Furthermore, the indicator system can be combined with the information platform in practice to realize effective monitoring and prediction of relevant data.

The study has two main limitations, and future studies are suggested to consider and address these limitations. First, the data used in this study were collected from China, and although Chinese interviewees have accumulated rich experiences in the management of steel structure construction, the data sample can be further extended to practitioners in countries with special national conditions. More extensive data will optimize the results. In addition, in the absence of experimental data, the questionnaire survey provides a feasible method to examine the proposed topic in this research. Nevertheless, as the questionnaire survey relies heavily on experts’ subjective opinions, more objective data should be used to in future similar studies.

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