Establishment of a Sustainability Assessment System for Bridges

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Abstract: In this paper, with the motivation of “green” and “sustainability” for bridge projects, ten key indicators were selected to establish a reliable and applicable sustainability assessment system. It is also expecting the civil infrastructure to be developed more ecologically, environmentally, and friendly by applying the proposed assessment system. The data collection method in this research is questionnaire-based expert interviews. The questionnaire results were well analyzed and calculated for the key indicators’ weights by adopting the top two boxes theory (TTBT) and multiple attribute value theory (MAVT). Consequently, the sustainability assessment system for green civil infrastructure (SASGCI) was established to evaluate infrastructure projects’ sustainability achievements. In this study, the authors conclude the weights of ten key indicators for bridges as follows: risk mitigation and reliability: 15.3%, durability: 15.1%, landscape: 11.5%, ecology: 10.6%, benefit and function: 9.7%, environmental protection and carbon emissions reduction: 9.5%, waste reduction: 8.5%, energy-saving: 7.1%, creativity: 7.0%, and humanities and culture reservation: 5.6%. An example of a scenic bridge in Taiwan is presented to demonstrate the applicability of the established SASGCI for sustainability evaluation. The result indicates that the evaluation system is successful.

Keywords: bridge engineering; sustainable development; sustainability assessment system for green civil infrastructure (SASGCI); sustainability civil infrastructure; certificate grade

1. Introduction

In recent years, owing to global warming, sustainability issues have been wildly concerned and discussed in all fields of engineering projects. The “sustainable” and “green” considerations may include environment protection, carbon emission reduction, energy-saving, green materials, safety assurance, risk mitigation, reliability, ecology, waste reduction, durability, benefit, landscape, humanities, culture preservation, and creativity. In the past, specific sustainability indicators for infrastructures have been proposed [1,2]. Key assessment indicators have been established to evaluate sustainability issues in engineering fields [3–6]. The primary purpose of performing sustainability research is to prevent harmful impacts on the environment during the project life cycle. The harmful impacts include global warming caused by the increase of CO2 emission, depletion of resources, and adverse effects on the environment and ecology due to construction. Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs [7]. Green civil infrastructure is a civil engineering system or facility environmentally friendly and is least damaging to the environment and society in the project life cycle [8]. Some infrastructure projects performed sustainability practices during the development and the life cycle [9–11]. Efforts in sustainability draw attention and public support for infrastructures such as residential houses, roads, highways, bridges, tunnels, water supply, sewers, electrical grids, and telecommunications, just to
name a few. Specifically, sustainable and green infrastructures are being emphasized through designs and constructions that support long-term sustainability [9]. Sustainable and green civil infrastructure, including bridges, may contain the following criteria [12–15]:

- Maintain safety management, risk mitigation, and reliability during the life cycle.
- Minimize the CO$_2$ emission during the life cycle and harmful impacts on the environment and ecology.
- Optimize the landscape for the project developed zone.
- Maximize the benefit/function of project development.
- Reduce the waste production and try to possibly recycle the wastes during the life cycle.
- Save energy during the life cycle.
- Extend the durability of the project.
- Preserve the local culture and maintain the social conscience.
- Encourage creativity.
- Keep a reasonable cost during the life cycle.

The authors aim to establish an assessment system to evaluate civil infrastructure to achieve the above sustainable criteria [16–18]. The establishment of this assessment system is hoped to provide a functional and reliable tool to help engineers determine civil infrastructure development. It is also expecting the civil infrastructure could be developed more ecologically, environmentally, and friendly. This assessment system, “sustainability assessment system for green civil infrastructure (SASGCI)” [19], is developed through expert interviews and quantitative study by adopting the multiple attribute value theory (MAVT) [20] and top two boxes theory (TTBT) [21–24] methods. This study aims to determine the weight of importance of each key indicator and to form an evaluation system to assess the bridge projects.

In this research, with in-depth discussions with some experts, the author selects ten key indicators, which will be described in detail in Section 3, for the assessment of sustainability for infrastructures. The selection of these ten key indicators is based on the importance of these indicators in sustainable civil infrastructures, as shown in Figure 1. Some issues in green buildings, such as health, sewage and waste disposal facility improvement, indoor environment, and so on, are not significant concerns and, therefore, are not included in key indicators of assessment for green sustainable civil infrastructures.

![Figure 1. Key indicators of "green buildings" and "sustainable civil infrastructures".](image-url)
2. Methodology
2.1. Questionnaire-Based Expert Interview

In this paper, the researchers propose sustainability key indicators for the assessment system of bridges. In addition to the reference of the published documents, the expert interview is the central part of this research. The experts were chosen from consulting engineers, construction engineers, professors, and government officials in Taiwan. The background of experts covers structures, bridges, geotechnical engineering, construction management, slopes, ecology, environment, transportation, pavement, safe/risk management, energy, and so on. The average seniority of these experts is 27 years. The authors executed the interviews with a detailed explanation of the questionnaire. The questionnaire contains the ten key indicators and the 48 related evaluation items and covers four essential elements of civil infrastructures, i.e., bridge, tunnel, slope, and building. It also covers the project’s life cycle, including design, construction, operation, and demolition. Figure 2 shows the ecology part of the questionnaire.

Table 1. Evaluation items for ten key indicators [19].

| Key Indicators                                         | Evaluation Items                                                                 |
|--------------------------------------------------------|-----------------------------------------------------------------------------------|
| Risk Mitigation and Reliability                        | • Providing large enough safety factor in the design                             |
|                                                        | • Considering a second disaster prevention mechanism for the life cycle of the facility |
|                                                        | • External review/approval mechanism for design results                          |
|                                                        | • Avoiding geologically sensitive areas                                          |
|                                                        | • Design and construction documents approved by certified professional engineers |
|                                                        | • Establishment of risk mitigation mechanism                                     |
|                                                        | • Minimization of the interference to the flooding and disaster protection       |
|                                                        | • Establishment of feasible operations management system to ensure user safety  |
|                                                        | • Periodical disaster prevention drill in the life cycle                         |
| Ecology                                                | • Ecological environment investigation, data collection, and impact assessment    |
|                                                        | • Site preservation and indicative trees protection                              |
|                                                        | • Ecological environment monitoring                                             |
|                                                        | • Selection of low impact construction methods and preservation of biodiversity and animal habitat integrity. Establishment of safety facilities for animals |
| Environmental Protection and Carbon Emissions Reduction (ER and CER) | • Environmental impact assessment                                               |
|                                                        | • Monitoring of carbon emission in the life cycle                                |
|                                                        | • Reduction of the carbon emission in the life cycle                             |
|                                                        | • Adoption of the construction methods and materials with low-carbon emission   |
|                                                        | • Construction methods and procedures with low air pollution.                    |
|                                                        | • Adoption of permeable pavement to preserve water                               |
| Energy Saving                                          | • Adoption of green energy (e.g., solar energy, wind energy)                     |
|                                                        | • Selection of energy-saving materials and construction methods                  |
|                                                        | • Use of local materials to save energy and to reduce carbon emission            |
|                                                        | • Use of energy-saving machinery to reduce energy consumption                    |
|                                                        | • Design and selection of energy-saving electrical and mechanical equipment      |
|                                                        | • Periodic maintenance for equipment in the life cycle                           |
| Waste Reduction                                        | • Use of recyclable and environmentally friendly materials                       |
|                                                        | • Adoption of waste reduction construction methods (e.g., precast, modularization) |
|                                                        | • Use of industrial or construction by-product (e.g., fly ash, ground-granulated blast-furnace slag, reservoir silt) |
|                                                        | • Water resource recycling                                                       |
|                                                        | • Adoption of the public soil exchange mechanism                                |
|                                                        | • Balance of cut and fill at the same site                                       |
Table 1. Cont.

| Key Indicators          | Evaluation Items                                                                 |
|-------------------------|----------------------------------------------------------------------------------|
| **Durability**          | • Durable structure design                                                       |
|                         | • Use of durable materials                                                        |
|                         | • Establishment of quality assurance measures to increase the life expectancy of  |
|                         |   the structures                                                                  |
|                         | • Adoption of design that facilitates easy maintenance                            |
| **Benefit and function**| • The satisfaction of the design function                                          |
|                         | • Boost of the local economy and increase of the job market                       |
|                         | • Enhancement of the design/construction/operation quality and ability             |
|                         | • Shortening of construction duration to maximize the benefit                      |
|                         | • Cost down in the life cycle                                                     |
| **Landscape**           | • Consideration of local culture in the structure design                          |
|                         | • Beautification of structure and landscape. Design of structure for landscape fusion |
|                         | • Selection of low impact construction methods and preservation of biodiversity and |
|                         |   animal habitat integrity. Establishment of safety facilities for animals        |
| **Humanities and Culture**| • Provision of participation and communication to the public                       |
|                         | • Promotion of participation and communication to the public                      |
|                         | • Establishment of feasible operations management system to ensure user safety     |
|                         | • Periodical disaster prevention drill in the life cycle                           |
| **Creativity**          | • Introduction of new materials, new construction methods, new technologies, and  |
|                         |   so on                                                                           |
| **Ecology**             | • Ecological environment investigation, data collection, and impact assessment    |
|                         | • Site preservation and indicative tree protection                                 |
|                         | • Ecological environment monitoring, data collection, and impact assessment       |
| **Sustainability**       | • Protection of historical sites and cultural relics                               |
| **Cost down in the life cycle** | • Adoption of design that facilitates easy maintenance                           |

In addition to bridges, tunnels, and slopes, buildings are also included in the questionnaire for comparison purposes. After the researchers provided a detailed description, the experts can select from the five selections of the Likert scale form to represent the importance of each evaluation item in each stage. Selection of (4) points represents the highest importance, (3) points represents important, (2) points represent normal, (1) points represent low importance, and (0) points represent not important.
highest importance, and (0) points represents the lowest importance. Some “black-out” parts are presented because they are not related to the evaluation item in the corresponding stage. The expert is not requested to answer in these parts. The authors establish the sustainability assessment system for bridges, tunnels, slopes, and buildings with the analysis of the questionnaire results gathered from 47 experts. In this paper, only the results of “bridges” will be presented.

2.2. Analysis of Questionnaire Data

In recent years, a couple of techniques have been adopted to determine the conclusion for the results of the questionnaire from expert review [23], such as the top two boxes theory (TTBT) [21–24] and multiple attribute value theory (MAVT) [20]. In this paper, a combination of the TTBT and MAVT is applied to calculate and analyze the questionnaire results.

2.2.1. Top Two Boxes Theory (TTBT)

The “top box” means the highest score of the questionnaire’s selections, and the “top-two box” means the highest and second scores of the questionnaire choices. The “box” is the selection of the questionnaire by the participants. For example, when the scores of the questionnaire range from 5 points to 1 point, the top two boxes mean 5 points and 4 points. The top two boxes score means that the score is calculated with the percentage of 5 points and 4 points in the sampling population. Reporting the top two boxes score has the advantage of providing more variation in the data. Thus, it is easier to identify and emphasize the actual results of the selections among the multiple attributes. The top two box score is often relatively high, such that it sometimes leads to higher accuracy because its high value seems to indicate that respondents are very satisfied [21–24].

2.2.2. Multiple Attribute Value Theory (MAVT)

Multiple attributes determination aims to calculate the weights from the evaluation items of multiple attributes at different levels [25]. According to Buede and Maxwell [26], MAVT addresses the relative weights of obtaining a specific level of performance [20].

MAVT, in order to serve as a multiple criteria decision-making technique, aims to provide support for the determination of multiple attributes at different levels by developing a scoring system [27,28]. The technique has three steps: (1) determine the relative weight of each attribute; (2) calculate the importance weight of each attribute; and (3) integrate the weights for the key attributes in the first level with the weights obtained from the sub-levels. The final weights distribution for crucial attributes in the first level is calculated for the summation of 1.0 as well.

Basically, analytic hierarchy process (AHP) is a popular technique for the questionnaire analysis. It is proposed to adopt MAVT and TTBT owing to the inefficiency of pairwise comparisons in the AHP analysis. By adopting the MAVT and TTBT techniques and related formulas, the researchers performed the statistical analyses and calculated each key indicator and evaluation item’s rates and weights.

The “formula, f(x)” function provided by Microsoft Excel is a powerful tool for calculation of the rates and weights. Key in the correct equations to the specified cell concerning other corresponding cells, and the calculation results are obtained immediately. Furthermore, the statistics chart can be created directly along with equations [29–31].

2.2.3. Definition of Each Level’s Weight

Using the statistical data obtained from the questionnaire and MAVT as tools of analysis processes, some specified equations, which are introduced in the following sections, are applied to calculate the rates and weights in each level of the SASGCI. The authors divided the weight calculation processes into three levels, i.e., the ten key indicators for level 1, the evaluation items for level 2, and the four stages of life cycle for level 3. The subscripts of level 1 are presented by “i”, level 2 by “j”, and level 3 by “k”. $w_{ijk}$ denotes
the weight of the stage “k” of the evaluation item “j” for the key indicator “i”. For example, $W_{143}$ means the weight of the third stage (operation stage) of the fourth evaluation item (avoiding geologically sensitive areas) for the first key indicator (risk mitigation and reliability). To simulate the weights of the SASGCI as a 3D matrix, the $W_{ijk}$ is located in the corresponding location of this matrix. Figure 3 shows the 3D diagram of the $W_{ijk}$, and point A denotes the location of $W_{243}$.

![3D diagram of the Wijk matrix](image)

**Figure 3.** 3D diagram of the $W_{ijk}$ (point A denotes the location of $W_{243}$).

### 3. Development of Assessment System for Green Civil Infrastructure Projects

#### 3.1. Development of Key Indicators for Bridges

Some important issues are taken into consideration as the “key indicators” of the sustainability assessment system for green civil infrastructure (SASGCI). It is the first level of the assessment system. Each indicator should contain some related evaluation items as the second level of the assessment system. For consideration of a project’s entire life cycle, it is necessary to cover four stages, which include design, construction, operation, and demolition, to be level three of the system [19]. Figures 4 and 5 show the development and structure of the SASGCI, respectively.

![Development of the assessment system](image)

**Figure 4.** Development of the assessment system [19].

**Discuss the key indicators** that should be contained in the assessment system. **Confirm the related evaluation items** for each indicator. **Consider the stages for the entire lifecycle:** design, construction, operation, and demolition.
By performing an in-depth discussion with experts, the researchers propose ten sustainable key indicators for bridges as follows:

- Risk mitigation and reliability
- Ecology
- Environmental protection and carbon emissions reduction (ER and CER)
- Energy saving
- Waste reduction
- Durability
- Benefit and function
- Landscape
- Humanities and culture preservation (H&C)
- Creativity

Table 1 illustrates the evaluation items for each key indicator. Figure 6 shows the research framework of SASGCI [19].

The key sustainability indicators of SASGCI contain two major parts as follows:

- Weight determination for each key indicator.
- Project evaluation for sustainability achievement.

The following sections describe the detailed processes for establishing the assessment system.

3.2. Questionnaire Results Analysis
3.2.1. Expertise and Education of the Experts

The experts’ interview is the starting process to establish the key indicators for SASGCI. The interviews were performed from June 2018 to July 2019. Figures 7–9 show the different disciplines, occupations, and educational backgrounds of experts, respectively.
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3.2.2. Weights for Level 3: Stages of Project Life Cycle

In general, the life cycle of an engineering project can be divided into four stages, i.e., design, construction, operation and maintenance, and demolition. In the questionnaire, each expert was requested to determine the relative weight ratio, R\textsubscript{a,k}, i.e., the relative importance among the four stages of the life cycle. The mean (average) of the R\textsubscript{a,k} provided...

Figure 6. Research framework of the assessment system [19].

Figure 7. Diagram of experts’ disciplines (note: CM denotes construction management).

Figure 8. Distribution of experts’ occupations.
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In general, the life cycle of an engineering project can be divided into four stages, i.e., design, construction, operation and maintenance, and demolition. In the questionnaire, each expert was requested to determine the relative weight ratio, $R_{ak}$, i.e., the relative importance among the four stages of the life cycle. The mean (average) of the $R_{ak}$ provided by all the experts is represented as $R_k$ ($k = 1$ to 4). Higher $R_k$ denotes the higher importance of any of the stages of sustainability performance. The rate $R_k$ of the four stages is calculated using Equation (1).

\[
R_k = \frac{1}{n} \times \left( \sum_{k=1}^{n} R_{ak} \right) \tag{1}
\]

where $n$ indicates the total number of experts that participated. $k$ ranges from 1 to 4, indicating the design, construction, operation, and demolition stages, respectively.

Besides, by adopting the TTBT, the authors propose Equation (2) for the calculation of the ratio of the top two selection (4 and 3 points) $T_{2k}$ as follows:

\[
T_{ijk} = \left( \frac{n_3 + n_4}{n} \right) \times 100\% \tag{2}
\]

- a. “$i$” varies from 4 to 9, depending on the number of evaluation items in each key indicator;
- b. “$i$” ranges from 1 to 10, indicating the ten key indicators;
- c. “$n_x$” ($x = 4$ and 3) shows the number of experts who give $x$ points ($x = 4$ and 0) of the importance rate of level 3;
- d. “$n$” indicates the total number of experts who participated.

After the determination of the weight ($R_k$) of importance and ratio ($T_{2k}$) of the top two boxes value, the experts are requested to assign the importance rate points (from 4 to 0) for each evaluation item. Each item is separated into four different project stages, i.e., design, construction, operation, and demolition stages. The experts are requested to assign from 4 points (most important) to 0 points (least significant) for each stage. The importance weights of each stage for level 3, $W_{ijk}$, are calculated using Equation (3).

\[
W_{ijk} = \left[ \frac{1}{n} \times (4 \times n_4 + 3 \times n_3 + 2 \times n_2 + 1 \times n_1 + 0 \times n_0) \right] \times R_k \times T_{2k} \tag{3}
\]

3.2.3. Weight for Level 2: Evaluation Items

In level 2, the researchers simplify the $W_{ijk}$ by calculating the weights of four stages to that of each evaluation item, $W_{ij}$, as shown in Equation (4). The subscripts of level 1 are presented by “$i$” and level 2 by “$j$”. $W_{ij}$ denotes the weight of the evaluation item “$i$” for the key indicator “$i$”. For example, $W_{14}$ means the weight of the fourth evaluation
item (avoiding geologically sensitive areas) for the first key indicator (risk mitigation and reliability).

\[ W_{ij} = \frac{\sum_{k=1}^{y} W_{ijk}}{y} \]  

(4)

The mean of \( W_{ij} \) for each key indicator, denoted as \( S_i \), can be calculated using Equation (5).

\[ S_i = \frac{\sum_{j=1}^{z} W_{ij}}{z} \]  

(5)

where “\( z \)” varies from 4 to 9, depending on the number of evaluation items in each key indicator.

### 3.2.4. Weight for Level 1: Key Indicators

In level 1, the researchers calculate the relative weight among all sustainability key indicators. The researchers add the \( S_i \) of all the key indicators to get the \( S_{\text{total}} \), as shown in Equation (6).

\[ S_{\text{total}} = \sum_{i=1}^{10} S_i \]  

(6)

where \( i \) ranges from 1 to 10, denoting the number of key indicators.

Following the calculation results of \( S_i \) and \( S_{\text{total}} \), it can reach the weight \( W_i \) of level 1. The subscript of level 1 is presented by “1”. \( W_i \) denotes the weight of key indicator “1”. For example, \( W_1 \) means the weight of the first key indicator (risk mitigation and reliability). It is the final result of the assessment system. The calculation of \( W_i \) is shown as Equation (7).

\[ W_i = \frac{S_i}{S_{\text{total}}} \]  

(7)

Based on the questionnaire results gathered from the experts’ interview, this research analyzes these reliable data by adopting the Equations (1)–(7) to calculate the weights of sustainability key indicators for bridges, tunnel, and slopes, which are described in the following sections.

### 3.3. Calculation for Weights of Sustainability Key Indicators for Bridges

This section presents an example with the detailed step-by-step calculation for weights of three levels of the key indicators. The “ecology indicator” is chosen for this demonstration. The other key indicators follow the same steps to calculate the weights and are not duplicated for simplicity.

#### 3.3.1. Relative Weight of the Four Stages

As mentioned in Section 3.2.2, the relative importance among the four stages of the life cycle might be evaluated. The mean (average) of the \( R_{ak} \) provided by all the experts is represented as \( R_k \) (\( k = 1 \) to 4). The weight of importance, \( R_k \), is calculated by adopting Equation (1).

From the questionnaire result on this part, a total of 47 experts expressed their determination for the relative weight of the four stages.

The “\( R_k \)” of the four stages for “bridges” is calculated by adopting Equation (1) as the mean of the expert questionnaire results and is shown in Table 2.

Table 2. Weight of importance of the four stages for bridges.

| Equation | Design | Construction | Operation | Demolition |
|----------|--------|--------------|-----------|-----------|
| \( R_k = (1/n) \times \sum R_{ak} \) | 38.68% | 30.95% | 19.56% | 10.80% |
Table 2 shows that the relative importance from the design, construction, operation, to demolition stages gradually reduced. It indicates the design stage $R_1$ is the most important one, which leads to the sustainability achievements of a newly developed bridge project from the beginning.

By basic statistics data of questionnaire results, the authors note the number of $n_k$ for four stages of each evaluation item of the “ecology” indicator, as shown in Table 3.

### Table 3. Number of $n_k$ for four stages of each evaluation items of the “ecology” indicator.

| Evaluation Items                                         | Stages               | $n_4$ | $n_3$ | $n_2$ | $n_1$ | $n_0$ | Mean |
|---------------------------------------------------------|----------------------|-------|-------|-------|-------|-------|------|
| Ecological environment investigation, data collection,   | Design               | 28    | 13    | 4     | 2     | 0     | 3.4  |
| and impact assessment                                    | Construction         | 15    | 15    | 8     | 9     | 0     | 2.8  |
|                                                          | Operation            |       |       |       |       |       |      |
|                                                          | Demolition           |       |       |       |       |       |      |
| Site preservation and indicative trees protection        | Design               | 17    | 19    | 5     | 6     | 0     | 3.0  |
|                                                          | Construction         | 10    | 20    | 11    | 3     | 3     | 2.7  |
|                                                          | Operation            | 6     | 12    | 15    | 9     | 5     | 2.1  |
|                                                          | Demolition           |       |       |       |       |       |      |
| Ecological environment monitoring                        | Design               | 15    | 16    | 10    | 4     | 2     | 2.8  |
|                                                          | Construction         | 18    | 19    | 5     | 5     | 0     | 3.1  |
|                                                          | Operation            | 14    | 15    | 9     | 6     | 3     | 2.7  |
|                                                          | Demolition           |       |       |       |       |       |      |
| Selection of low impact construction methods and         | Design               | 27    | 11    | 7     | 2     | 0     | 3.3  |
| preservation of biodiversity and animal habitat integrity.| Construction         | 26    | 16    | 3     | 6     | 0     | 3.4  |
|                                                          | Operation            | 13    | 11    | 15    | 6     | 2     | 2.6  |
|                                                          | Demolition           |       |       |       |       |       |      |

3.3.2. The Detailed Calculation Steps for the Weight of Level 3—Four Stages: $W_{ijk}$

The first evaluation item of indicator “ecology” is the “ecological environment investigation, data collection, and impact assessment”, as shown in Tables 1 and 3. The “design” stage gathers the questionnaire results for the determinations are $n_4$ (4 points): 28 selected, $n_3$ (3 points): 13 selected, $n_2$ (2 points): 4 selected, $n_1$ (1 point): 2 selected, and $n_0$ (0 points): 0 selected.

By adopting Equation (3), the mean (average) of this stage is listed as follows:

- Mean = \(\frac{(28 \times 4 + 13 \times 3 + 4 \times 2 + 2 \times 1 + 0 \times 0)}{47} = 3.4\)

By adopting Equation (2), the top two boxes ratio of this stage is listed as follows:

- $T_{211} = \frac{(28 + 13)}{47} = 87.23\%$

By adopting Equation (3), the importance weights of each stage for level 3, $W_{ijk}$, are calculated as follows:

- $W_{211} = 3.4 \times 38.68\% \times 87.23\% = 1.16$ ($W_{211}$ denotes second the key indicator, first evaluation item, and first stage)

Followed the same calculation steps, the “construction” stage of the first evaluation item of indicator “ecology”, which is the “ecological environment investigation, data collection, and impact assessment”, is calculated and listed as follows:

- Mean = 2.8, $T_{212} = 63.83\%$, $W_{212} = 0.55$

By adopting the same calculation processes, the authors obtain the “design” stage of the second evaluation item of indicator “ecology”, which is the “site preservation and indicative trees protection”, which is calculated and listed as follows:

- Mean = 3.0, $T_{221} = 76.60\%$, $W_{222} = 0.89$

Furthermore, by adopting the same calculation processes, the researchers obtain the “construction” stage of the second evaluation item of indicator “ecology”, which is the “site preservation and indicative trees protection”, which is calculated and listed as follows:
• Mean = 2.7, $T_{222} = 63.83\%$, $W_{222} = 0.53$

Furthermore, by adopting the same calculation processes, the authors obtain the “operation” stage of the second evaluation item of indicator “ecology”, which is the “site preservation and indicative trees protection”, which is calculated and listed as follows:

• Mean = 2.1, $T_{223} = 38.30\%$, $W_{223} = 0.16$

The “demolition” stage is not related to the evaluation item of “site preservation and indicative trees protection”. The evaluations of these two stages are kept blank, and the $W_{224}$ is not taken into calculation.

The calculation results of the four stages for all evaluation items of the “ecology” indicator are shown in Table 4.

| Evaluation Items                                                                 | Stages       | Mean   | Top Two Ratio | $W_{2jk}$ |
|---------------------------------------------------------------------------------|--------------|--------|---------------|-----------|
| Ecological environment investigation, data collection, and impact assessment     | Design       | 3.4    | 87.23%        | 1.16      |
|                                                                                 | Construction | 2.8    | 63.83%        | 0.55      |
|                                                                                 | Operation    | 2.1    | 38.30%        |           |
|                                                                                 | Demolition   |        |               |           |
| Site preservation and indicative trees protection                               | Design       | 3.0    | 76.60%        | 0.89      |
|                                                                                 | Construction | 2.7    | 63.83%        | 0.53      |
|                                                                                 | Operation    | 2.1    | 38.30%        | 0.16      |
|                                                                                 | Demolition   |        |               |           |
| Ecological environment monitoring                                               | Design       | 2.8    | 65.96%        | 0.72      |
|                                                                                 | Construction | 3.1    | 78.72%        | 0.75      |
|                                                                                 | Operation    | 2.7    | 61.70%        | 0.32      |
|                                                                                 | Demolition   |        |               |           |
| Selection of low impact construction methods and preservation of biodiversity and animal habitat integrity. Establishment of safety facilities for animals | Design       | 3.3    | 80.85%        | 1.04      |
|                                                                                 | Construction | 3.4    | 89.36%        | 0.94      |
|                                                                                 | Operation    | 2.6    | 51.06%        | 0.26      |
|                                                                                 | Demolition   |        |               |           |

3.3.3. The Detailed Calculation Steps for the Weights of Level 2—Evaluation Items: $W_{ij}$

Following the above steps, the calculation for the weight of level 2 $W_{ij}$ is done by adopting of Equation (4). The level 3 weights $W_{211}$ and $W_{212}$ of the first evaluation item, which is “ecological environment investigation, data collection, and impact assessment” of the key indicator “ecology”, were calculated in the above steps. They are 1.16 and 0.55, respectively. From Equation (4), the researchers obtained the level 2 weight of the first evaluation item $W_{21}$ as follows:

• $W_{21} = (1.16 + 0.55)/2 = 0.85$

Moreover, the level 3 weights $W_{221}$, $W_{222}$, and $W_{223}$ of the second evaluation item, which is “site preservation and indicative trees protection” of the key indicator “ecology”, were calculated. They are 0.89, 0.53, and 0.16, respectively. From Equation (4), the researchers obtained the level 2 weight of the second evaluation item $W_{22}$ as follows:

• $W_{22} = (0.89 + 0.53 + 0.16)/3 = 0.52$

Besides, the level 3 weights $W_{231}$, $W_{232}$, and $W_{233}$ of the third evaluation item, which is “ecological environment monitoring” of the key indicator “ecology”, were calculated. They are 0.72, 0.75, and 0.32, respectively. From Equation (4), the researchers obtained the level 2 weight of the third evaluation item $W_{23}$ as follows:

• $W_{23} = (0.72 + 0.75 + 0.32)/3 = 0.59$

Furthermore, the level 3 weights $W_{241}$, $W_{242}$, and $W_{243}$ of the fourth evaluation item, which is “selection of low impact construction methods and preservation of biodiversity, animal habitat integrity, and the establishment of safety facilities for animals”, were cal-
culated. They are 1.04, 0.94, and 0.26, respectively. From Equation (4), the researchers obtained the level 2 weight of the fourth evaluation item $W_{24}$ as follows:

- $W_{24} = (1.04 + 0.94 + 0.26)/3 = 0.75$

Now, the researchers obtain the summation of $W_{ij}$ as $S_i$ by adopting Equation (5) as follows:

- $S_2 = (0.85 + 0.52 + 0.59 + 0.75)/4 = 0.679$

The calculation results for weights $W_{ij}$ and its mean of summary $S_i$ of the second level for the key indicator “ecology” are listed in Table 5.

**Table 5. Calculation results for weights $W_{ij}$ and its mean of summary $S_i$ of the second level for the “ecology” indicator.**

| Evaluation Items | Stages              | $W_{2jk}$ | $W_{2j}$ | $S_2$ |
|------------------|---------------------|-----------|----------|-------|
| Ecology          | Design              | 1.16      | 0.85     | 0.679 |
|                  | Construction        | 0.55      |          |       |
|                  | Operation           |           |          |       |
|                  | Demolition          |           |          |       |
| Site preservation and indicative trees protection | Design | 0.89 |  |
|                  | Construction        | 0.53      |          |       |
|                  | Operation           | 0.16      | 0.52     | 0.679 |
|                  | Demolition          |           |          |       |
| Ecological environment monitoring | Design | 0.72 |  |
|                  | Construction        | 0.75      |          |       |
|                  | Operation           | 0.32      | 0.59     |       |
|                  | Demolition          |           |          |       |
| Selection of low impact construction methods and preservation of biodiversity and animal habitat integrity. Establishment of safety facilities for animals | Design | 1.04 |  |
|                  | Construction        | 0.94      | 0.75     |       |
|                  | Operation           | 0.26      |          |       |
|                  | Demolition          |           |          |       |

3.3.4. The Detailed Calculation Steps for the Weights of Level 1—Key Indicators: $W_i$

By adopting Equations (1)–(4), the researchers obtain the weights $W_{ij}$, which is the mean of summary $S_i$ of the second level for all sustainability key indicators and is listed in Table 6.

**Table 6. Weights $W_{ij}$ and the mean of summary $S_i$ of the second level for all sustainability key indicators.**

| Sustainability Key Indicators | Evaluation Items                                                                 | $W_{ij}$ | $S_i$ |
|------------------------------|----------------------------------------------------------------------------------|----------|-------|
| Risk Mitigation and Reliability | Providing large enough safety factor in the design                               | 1.36     | 0.985 |
|                              | Considering a second disaster prevention mechanism for the life cycle of the facility | 0.75     |       |
|                              | External review/approval mechanism for design results                           | 0.79     |       |
|                              | Avoiding geologically sensitive areas                                           | 1.27     |       |
|                              | Design and construction documents approved by certified professional engineers | 1.14     |       |
|                              | Establishment of risk mitigation mechanism                                      | 0.81     |       |
|                              | Minimization of the interference to the flooding and disaster protection         | 0.83     |       |
|                              | Establishment of feasible operations management system to ensure user safety     | 0.92     |       |
|                              | Periodical disaster prevention drill in the life cycle                           |          |       |
| Ecology                      | Ecological environment investigation, data collection, and impact assessment      | 0.85     | 0.679 |
|                              | Site preservation and indicative trees protection                                | 0.52     |       |
|                              | Ecological environment monitoring                                                | 0.59     |       |
Table 6. Cont.

| Sustainability Key Indicators | Evaluation Items                                                                 | $W_{ij}$ | $S_i$ |
|-------------------------------|-----------------------------------------------------------------------------------|----------|-------|
| **Environmental Protection and Carbon Emissions Reduction** | Selection of low impact construction methods and preservation of biodiversity and animal habitat integrity. Establishment of safety facilities for animals | 0.75     |       |
|                               | Environmental impact assessment                                                   | 0.58     |       |
|                               | Monitoring of carbon emission in the life cycle                                   | 0.48     |       |
|                               | Selection of low carbon emission materials                                        | 0.73     | 0.608 |
|                               | Construction methods and procedures with low air pollution Reduce the carbon emission in the life cycle and select the construction methods with low-carbon emissions | 0.61     |       |
|                               | Adoption of permeable pavement to preserve water                                  | 0.64     |       |
| **Energy Saving**             | Adoption of green energy (e.g., solar energy, wind energy)                        | 0.23     |       |
|                               | Selection of energy-saving materials and construction methods                      | 0.50     |       |
|                               | Use of local materials to save energy and to reduce carbon emission                | 0.60     |       |
|                               | Use of energy-saving machinery to reduce energy consumption                        | 0.45     |       |
|                               | Design and selection of energy-saving electrical and mechanical equipment          | 0.47     |       |
|                               | Periodic maintenance for equipment in the life cycle                               | 0.50     |       |
| **Waste Reduction**           | Use of recyclable and environmentally friendly materials                           | 0.53     |       |
|                               | Adoption of waste reduction construction methods (e.g., precast, modularization)   | 0.74     |       |
|                               | Use of industrial or construction by-product (e.g., fly ash, ground-granulated blast-furnace slag, reservoir silt) | 0.80     | 0.546 |
|                               | Water resource recycling                                                           | 0.07     |       |
|                               | Adoption of the public soil exchange mechanism                                     | 0.54     |       |
|                               | Balance of cut and fill at the same site                                          | 0.59     |       |
| **Durability**                | Durable structure design.                                                         | 1.01     | 0.968 |
|                               | Use of durable materials.                                                          | 0.95     |       |
|                               | Establishment of quality assurance measures to increase the life expectancy of the structures | 0.88     |       |
|                               | Adoption of design that facilitates easy maintenance.                              | 1.03     |       |
| **Benefit and Function**      | The satisfaction of the design function                                            | 0.81     | 0.623 |
|                               | Boost of the local economy and increase of the job market                          | 0.36     |       |
|                               | Enhancement of the design/construction/operation quality and ability               | 0.68     |       |
|                               | Shortening of construction duration to maximize the benefit                         | 0.77     |       |
|                               | Cost down in the life cycle                                                        | 0.48     |       |
| **Landscape**                 | Consideration of local culture in the structure design                            | 0.65     | 0.740 |
|                               | Beautification of structure and landscape. Design of structure for landscape fusion | 0.83     |       |
| **Humanities and Culture Preservation** | Provision of participation and communication to the public                         | 0.31     | 0.358 |
|                               | Safeguarding of social justice and care for minorities                            | 0.20     |       |
|                               | Protection of historical sites and cultural relics                                 | 0.57     |       |
| **Creativity**                | Introduction of new materials, new construction methods, new technologies, and so on | 0.46     |       |
|                               | Innovation in engineering project design                                           | 0.44     | 0.452 |
|                               | Establishment of incentives mechanism to encourage innovation                      | 0.52     |       |
|                               | Application of value engineering                                                  | 0.39     |       |
After this step, the researchers obtain \( S_i \) for ten sustainability key indicators. By adopting Equation (6), the researchers calculate \( S_{\text{total}} \) as follows:

\[
S_{\text{total}} = S_1 + S_2 + \ldots + S_{10} = 0.985 + 0.679 + 0.608 + 0.458 + 0.546 + 0.968 + 0.623 + 0.740 + 0.358 + 0.452 = 6.418
\]

Following the above calculation steps, the researchers adopt Equation (7) to calculate the importance weights of ten key indicators for level 1, \( W_i \):

\[
W_i = \frac{S_i}{S_{\text{total}}}
\]

The obtained \( W_i \) is the final result, “weight”, of the sustainability key indicators for “bridges”. Table 7 lists the calculated weights of level 3 (\( W_{ijk} \); four stages), level 2 (\( W_{ij} \); evaluation items), and level 1 (\( W_i \); ten key indicators) for “bridges”. Figure 10 shows the statistics chart for the weight of each key sustainability indicators for bridges.

**Table 7.** Calculated weights of level 3, level 2, and level 1 for bridges.

| Key Indicators                                  | Evaluation Items | \( W_{ijk} \) | \( W_{ij} \) | \( W_i \) |
|------------------------------------------------|------------------|--------------|--------------|----------|
| **Risk Mitigation and Reliability**            |                  |              |              |          |
| Item 1                                         | 1.36             | 0.55         | 0.47         | 1.36     |
| Item 2                                         | 1.25             |              |              | 0.75     |
| Item 3                                         | 0.79             |              |              | 0.79     |
| Item 4                                         | 1.27             |              |              | 1.27     |
| Item 5                                         | 1.33             | 0.96         |              | 1.14     |
| Item 6                                         | 1.11             | 1.08         | 0.23         | 0.81     |
| Item 7                                         | 1.29             | 0.99         | 0.19         | 0.83     |
| Item 8                                         | 1.20             |              | 0.65         | 0.92     |
| Item 9                                         |                  |              |              |          |
| **Ecology**                                    |                  |              |              |          |
| Item 1                                         | 1.16             | 0.55         |              | 0.85     |
| Item 2                                         | 0.89             | 0.53         | 0.16         | 0.52     |
| Item 3                                         | 0.72             | 0.75         | 0.32         | 0.59     |
| Item 4                                         | 1.04             | 0.94         | 0.26         | 0.75     |
| **Environmental Protection and Carbon Emissions Reduction (EP and CER)** | | | | |
| Item 1                                         | 1.28             | 0.61         | 0.28         | 0.17     |
| Item 2                                         | 0.72             | 0.72         | 0.36         | 0.12     |
| Item 3                                         | 1.21             | 0.65         | 0.33         | 0.73     |
| Item 4                                         | 1.10             | 0.96         | 0.19         | 0.18     |
| Item 5                                         | 0.95             | 0.69         | 0.28         | 0.64     |
| **Energy Saving**                              |                  |              |              |          |
| Item 1                                         | 0.26             | 0.17         | 0.27         | 0.23     |
| Item 2                                         | 0.97             | 0.30         | 0.22         | 0.50     |
| Item 3                                         | 0.60             | 0.00         | 0.00         | 0.60     |
| Item 4                                         | 0.68             | 0.21         |              | 0.45     |
| Item 5                                         | 0.68             | 0.32         | 0.40         | 0.47     |
| Item 6                                         | 0.69             | 0.32         | 0.49         | 0.50     |
| **Waste Reduction**                            |                  |              |              |          |
| Item 1                                         | 0.87             | 0.43         | 0.29         | 0.53     |
| Item 2                                         | 1.21             | 0.91         | 0.12         | 0.74     |
| Item 3                                         | 0.93             | 0.66         | 0.07         | 0.80     |
| Item 4                                         | 0.80             | 0.67         | 0.15         | 0.54     |
| Item 5                                         | 0.98             | 0.71         | 0.10         | 0.59     |
| Item 6                                         |                  |              |              |          |
| **Durability**                                 |                  |              |              |          |
| Item 1                                         | 1.51             | 0.51         |              | 1.01     |
| Item 2                                         | 1.43             | 0.84         | 0.57         | 0.95     |
| Item 3                                         | 1.06             | 0.98         | 0.60         | 0.88     |
| Item 4                                         | 1.41             | 0.66         |              | 1.03     |
| **Benefit and Function**                       |                  |              |              |          |
| Item 1                                         | 1.11             | 0.52         |              | 0.81     |
| Item 2                                         | 0.57             | 0.45         | 0.16         | 0.36     |
| Item 3                                         | 1.02             | 0.65         | 0.37         | 0.68     |
| Item 4                                         | 0.85             | 0.70         |              | 0.77     |
| Item 5                                         | 0.94             | 0.41         | 0.10         | 0.48     |
Table 7. Cont.

| Key Indicators                  | Evaluation Items | $W_{ijk}$ | $W_{ij}$ | $W_i$ |
|--------------------------------|------------------|----------|---------|-------|
| **Landscape**                  | Item 1           | 1.23     | 0.44    | 0.30  | 0.65  | 11.5% |
|                                | Item 2           | 1.43     | 0.71    | 0.33  | 0.83  |       |
| **Humanities and Culture (H and C)** | Item 3           | 0.61     | 0.31    | 0.23  | 0.08  | 0.31  | 5.6%  |
|                                | Item 4           | 0.33     | 0.19    | 0.07  | 0.20  |       |
|                                | Item 5           | 0.83     | 0.58    | 0.30  | 0.57  |       |
| **Creativity**                 | Item 1           | 0.82     | 0.50    | 0.06  | 0.46  |       |
|                                | Item 2           | 0.80     | 0.43    | 0.08  | 0.44  |       |
|                                | Item 3           | 0.84     | 0.62    | 0.12  | 0.52  |       |
|                                | Item 4           | 0.64     | 0.64    | 0.13  | 0.39  |       |

Figure 10. Statistics chart for the weight of each key sustainability indicator for bridges.

The authors divide the experts into different groups based on the occupation of the experts for the comparison of different results among these groups. There are four groups distinguished as the construction industry, consulting industry, government, and university. The relative weights $R_k$ by different groups of experts are shown in Figure 11.

Figure 11. Relative weights for bridges are determined by different groups of experts.

Furthermore, the weights of the ten indicators for this research obtained from the interview results from different groups of experts are analyzed to understand the different occupational engineers’ opinions on these civil and building projects’ sustainability issues. Figure 12 shows the charts of weights by different groups of experts’ interviews for bridge projects.
4. Sustainability Evaluation for Bridges Using the SASGCI

4.1. Calculation for the Evaluation

The central part of the evaluation system for sustainability achievement is the scoring sheet. Figure 13 shows the example of a scoring sheet for the key indicator, “ecology”.

![Figure 13. Example of the scoring sheet (ecology).]

The scoring sheet includes all the evaluation items of the key indicators with the design, construction, operation, and demolition stages. There are five categories: very good, good, not applicable (or average), bad, and very bad, in each scoring cell to evaluate each stage of each evaluation item’s performance. The evaluation team, who should be qualified or experienced experts, can choose one of the five selections to be his/her determination for the performance of the evaluation in each stage. Selection between the five options listed in the score sheet represents points as follows:

- Very good: 2 points.
- Good: 1 point.
- Not applicable (or average): 0 points.
- Bad: minus 1 point.
- Very bad: minus 2 points.

Considering that it might create a harmful effect on the sustainability issues during the life cycle of a bridge project, the authors propose the minus point to be the evaluator’s option.

If the evaluation is performed for a new bridge project, a detailed design is necessary for evaluation processes. If the evaluation is performed for a bridge that is under construction or in service, the achievement of sustainability can be evaluated directly based on its actual performance.

The obtained point $P_{ijk}$ from the selection will multiply with the level 3 weight $W_{ijk}$ to calculate each stage’s score for the evaluation items of ten key indicators. The score of each key indicator $P_i$ can be calculated by Equations (8) and (9).
• Very good: 2 points.
• Good: 1 point.
• Not applicable (or average): 0 points.
• Bad: minus 1 point.
• Very bad: minus 2 points.

Considering that it might create a harmful effect on the sustainability issues during the life cycle of a bridge project, the authors propose the minus point to be the evaluator’s option.

If the evaluation is performed for a new bridge project, a detailed design is necessary for evaluation processes. If the evaluation is performed for a bridge that is under construction or in service, the achievement of sustainability can be evaluated directly based on its actual performance.

The obtained point $P_{ijk}$ from the selection will multiply with the level 3 weight $W_{ijk}$ to calculate each stage’s score for the evaluation items of ten key indicators. The score of each key indicator $P_i$ can be calculated by Equations (8) and (9).

$$P_{ij} = \sum_{j=1}^{z} \left( \sum_{k=1}^{4} \left( P_{ijk} \times W_{ijk} \right) \right)$$

$$P_i = P_{ij} \times W \quad (9)$$

The final score (FS) of sustainability achievement is calculated after the summation of $P_i$. An adjust factor (AF) is defined to normalize the calculated score to the standard 0–100 scaling system. It is feasible to distinguish different grades of sustainability achievement. The FS can be calculated by Equation (10).

$$FS = \left( \sum_{j=1}^{10} P_i \right) \times AF \quad (10)$$

4.2. Evaluation Results

The following criteria are proposed to determine the grade certified from SASGCI:

The rating of the new project based on the SASGCI should meet each category’s score requirements as listed below. The following scores are tentatively assigned by the authors and can be modified later after the accumulation of more cases.

• Certified grade: the final score must be higher than 50 points.
• Bronze grade: the final score must be higher than 60 points.
• Silver grade: the final score must be higher than 70 points.
• Gold grade: the final score must be higher than 80 points.
• Diamond grade: the final score must be higher than 90 points.

To demonstrate the applicability of using the established SASGCI for the evaluation of sustainability, the authors present a case of a scenic bridge in Taiwan.

5. Case Study for Bridge Evaluation Using the SASGCI

In recent years, some bridge projects that developed in sustainable consideration are under construction in Taiwan. The researchers adopt the SASCBI for bridges established in this research to verify one bridge project under construction, Baimi Scenic Bridge (BSB) of Suhua Highway, in which the first author is in charge of construction management [9]. The researchers discuss the sustainability achievements by adopting SASGCI to realize the applicability of SASGCI for this individual case.

5.1. Baimi Scenic Bridge (BSB) of Suhua Highway

The Suhua Highway Improvement Project (SHIP) is located in eastern Taiwan, running in a north–south direction and connecting Suao (north end) and Hualien (south end). The
SHIP design started in 2008, and associated construction work commenced in 2013. It has served for transportation on 6 January 2020. The SHIP includes eight tunnels (a total of 24.5 km), thirteen bridges (8.5 km), and embankments/cuts (5.8 km), with a total length of 38.8 km. Some sustainability issues, including ecology, landscape, carbon reduction, and cultural preservation, have been taken into consideration for the life cycle of SHIP. The highway design incorporates local culture into the bridge architecture as well. It makes a pleasant addition to the landscape [9,17,32].

The authors highlight some primary sustainability practices and achievements of BSB as follows:

- **Carbon footprint inventory [33,34]:** A carbon footprint study indicates that improvements in material manufacturing processes and machinery operation can reduce carbon emission effectively during construction. In the BSB project, engineers focused on two portions: modifying the concrete mixture and improving the operation efficiency of equipment and machines.

- **Concrete mixture for carbon reduction [35]:** During the construction of BSB, the average carbon emission during cement production is 0.58 kgCO$_2$ e/kg. The concrete mixture was modified by substituting cement with recyclable materials such as coal fly ash (CFA) and ground-granulated blast-furnace slag (GGBFS), which was estimated in the design stage to reduce carbon emissions by 13–18% compared with the average value. In the completion of BSB, the carbon emission was found to be reduced by up to 34–43% from the original estimate.

- **Research on specified species [36]:** Construction activities can severely impact the habitats of local animal species. In the BSB construction, the biologists developed a research program to monitor changes in species’ population and health during the construction process. A severe variety of the quantity of the local species has caused the suspension of construction work to seek the reasons and resolve the ecology impact.

- **Ecological conservation:** The highway alignment was adjusted to avoid cutting or removing trees. The electrical control room for the tunnel was built underground to minimize any impact on the aboveground environment. Furthermore, efforts in design have been made to prevent animals from roadkill. Unique shading boards and light-cutting devices have been installed along the road edges to protect insects and other small flying species in the evening.

- **Landscape:** The highway passes by Baimimal Community, a village located between Suao and the Dongao tunnel. In Chinese, “Baimi” is the pronunciation of “rice”. The structure of Baimi Scenic Bridge is an extradosed bridge with a total length of 340 M. The engineers designed the pylon of the bridge to have a shape like a rice grain. This design incorporates local characteristics into the bridge architecture, making it a pleasant addition to the landscape. Figure 14 show on-site pictures of the BSB [19].

- **Cultural preservation:** During the excavation of the bridge foundation located near Hanbern, the engineers discovered ancient human ruins, including old tools and goods. This “Hanbern Historic Remains” is the relics of a Neolithic culture that was prevalent in this area 1100–1800 years ago. Because of the archaeological significance, the owner asked the bridge construction to stop for several years, until the archaeologist finished their on-site study.

### 5.2. The Detailed Calculation Steps for Evaluation of BSB of Suhua Highway

By applying the SASGCI, the constructed BSB was taken as an example to evaluate the sustainability achievements. The evaluation committee members were selected from the Ministry of Transportation and Communication of the Republic of China (ROC) experts. Some professors who are specialized in bridge and transportation engineering were also invited to the evaluation committee. After a detailed discussion among the evaluation committee members, the points of each stage for ten indicators are listed in Table 8.
Figure 14. Photos of the Baimi Scenic Bridge (BSB) [19].

Table 8. Sustainability evaluation sheet for Baimi Scenic Bridge (BSB).

| Risk Mitigation and Reliability                                      | Design | Construction | Operation | Demolition |
|---------------------------------------------------------------------|--------|--------------|-----------|------------|
| Providing large enough safety factor in the design                  | 2      | N/A          | N/A       | N/A        |
| Considering a second disaster prevention mechanism for the life cycle of the facility | 0      | 0            | 0         | N/A        |
| External review/approval mechanism for design results                | 0      | N/A          | N/A       | N/A        |
| Avoiding geologically sensitive areas                               | 0      | 0            | 0         | N/A        |
| Design and construction documents approved by certified professional engineers | 2      | 2            | N/A       | N/A        |
| Establishment of risk mitigation mechanism                          | 2      | 2            | N/A       | 0          |
| Minimization of the interference to the flooding and disaster protection | 2      | 2            | 2         | N/A        |
| Establishment of feasible operations management system to ensure user safety | 2      | N/A          | 2         | N/A        |
| Periodical disaster prevention drill in the life cycle              | 0      | 0            | 2         | N/A        |

| Ecology                                                             |        |              |           |            |
|---------------------------------------------------------------------|--------|--------------|-----------|------------|
| Ecological environment investigation, data collection, and impact assessment | 2      | 2            | N/A       | N/A        |
| Site preservation and indicative trees protection                    | 2      | 2            | 0         | N/A        |
| Ecological environment monitoring                                   | 2      | 2            | 0         | N/A        |
| Selection of low impact construction methods and preservation of biodiversity and animal habitat integrity. Establishment of safety facilities for animals | 2      | 2            | 2         | N/A        |

| Environmental Protection and Carbon Emissions Reduction (ER and CER) |        |              |           |            |
|---------------------------------------------------------------------|--------|--------------|-----------|------------|
| Environmental impact assessment                                     | 2      | 2            | 0         | 0          |
| Monitoring of carbon emission in the life cycle                      | 2      | 2            | 1         | 0          |
| Selection of low carbon emission materials                           | 2      | 0            | 1         | N/A        |
| Construction methods and procedures with low air pollution. Reduce the carbon emission in the life cycle and select the construction methods with low-carbon emissions | 2      | 2            | 0         | 0          |
| Adoption of permeable pavement to preserve water                     | 1      | 1            | 1         | N/A        |

| Energy Saving                                                       |        |              |           |            |
|---------------------------------------------------------------------|--------|--------------|-----------|------------|
| Adoption of green energy (e.g., solar energy, wind energy)          | 0      | 0            | 0         | N/A        |
| Selection of energy-saving materials and construction methods        | 2      | 2            | 0         | N/A        |
| Use of local materials to save energy and to reduce carbon emission  | 2      | 2            | 0         | N/A        |
| Use of energy-saving machinery to reduce energy consumption          | N/A    | 2            | N/A       | 0          |
Table 8. Cont.

| Category                                | Design | Construction | Operation | Demolition |
|-----------------------------------------|--------|--------------|-----------|------------|
| Design and selection of energy-saving electrical and mechanical equipment | 1      | 1            | 2         | N/A        |
| Periodic maintenance for equipment in the life cycle | 1      | 2            | 2         | N/A        |
| **Waste Reduction**                     |        |              |           |            |
| Use of recyclable and environmentally friendly materials | 2      | 2            | 2         | N/A        |
| Adoption of waste reduction construction methods (e.g., precast, modularization) | 0      | 1            | N/A       | 0          |
| Use of industrial or construction by-product (e.g., fly ash, ground-granulated blast-furnace slag, reservoir silt) | 2      | 2            | N/A       | N/A        |
| Water resource recycling                | 0      | 1            | 0         | 0          |
| Adoption of the public soil exchange mechanism | 2      | 2            | N/A       | 0          |
| Balance of cut and fill at the same site | 2      | 2            | N/A       | 0          |
| **Durability**                          |        |              |           |            |
| Durable structure design                | 2      | N/A          | 2         | N/A        |
| Use of durable materials                | 2      | 1            | 2         | N/A        |
| Establishment of quality assurance measures to increase the life expectancy of the structures | 2      | 2            | 2         | N/A        |
| Adoption of design that facilitates easy maintenance | 2      | N/A          | 2         | N/A        |
| **Benefit and Function**                |        |              |           |            |
| The satisfaction of the design function | 2      | N/A          | 2         | N/A        |
| Boost of the local economy and increase of the job market | 2      | 2            | 0         | 0          |
| Enhancement of the design/construction/operation quality and ability | 2      | 2            | 1         | N/A        |
| Shortening of construction duration to maximize the benefit | 2      | 2            | N/A       | N/A        |
| Cost down in the life cycle             | 2      | 2            | 1         | 0          |
| **Landscape**                           |        |              |           |            |
| Consideration of local culture in the structure design | 2      | 2            | 2         | N/A        |
| Beautification of structure and landscape. Design of structure for landscape fusion | 2      | 2            | 2         | N/A        |
| **Humanities and Culture Preservation (H and C)** |        |              |           |            |
| Provision of participation and communication to the public | 0      | 2            | 1         | 0          |
| Safeguarding of social justice and care for minorities | 1      | 1            | 2         | 0          |
| Protection of historical sites and cultural relics | 2      | 2            | 0         | N/A        |
| **Creativity**                          |        |              |           |            |
| Introduction of new materials, new construction methods, new technologies, and so on | 2      | 2            | 0         | 0          |
| Innovation in engineering project design | 2      | 1            | N/A       | 0          |
| Establishment of incentives mechanism to encourage innovation | 1      | 1            | 0         | 0          |
| Application of value engineering        | 0      | 0            | N/A       | N/A        |

The above blank cells (N/A) are not related to the execution of each evaluation item. The evaluation members are not requested to evaluate these stages during the evaluation work.

The next step to calculate the evaluation scores is to pick the determination of $P_{ijk}$ in the scoring sheet, as shown in Figure 11. The authors organize the SHIP director and some selected engineers to be the evaluation team members to determine the points $P_{ijk}$ of each stage (design, construction, operation, and demolition) for all evaluation items. In this bridge case, the authors take the “ecology” indicator to illustrate how the FS of bridges is calculated.

From Table 7, the $W_{ijk}$ for the “ecology” indicator of BSB are listed as shown in Table 9.
By adopting Equation (8), “ecology” is the second sustainability key indicator, so that the $P_{ij}$ could be showed as $P_{2j}$. Moreover, there are four evaluation items contained in this indicator, so that the $j$ could be shown as the number of 1 to 4 for representation of the four items. By adopting Equation (8), the $P_{2j}$ is calculated as follows:

- $P_{21} = 2.0 \times 1.16 + 2.0 \times 0.55 = 3.40$
- $P_{22} = 2.0 \times 0.89 + 2.0 \times 0.53 + 0.0 \times 0.16 = 2.83$
- $P_{23} = 2.0 \times 0.72 + 2.0 \times 0.75 + 0.0 \times 0.32 = 2.93$
- $P_{24} = 2.0 \times 1.04 + 2.0 \times 0.94 + 2.0 \times 0.26 = 4.49$
- $P_{2j} = 3.07 + 2.84 + 3.22 + 4.03 = 13.65$

By adopting Equation (9), the $P_2 = P_{2j} \times W_i$ ($W_2 = 10.6\%$ for bridges as listed in Table 7) is calculated as follows:

- $P_2 = 13.65 \times 10.6\% = 1.44$

The same steps could be applied to the other indicators and then $P_1$ to $P_{10}$ are listed as follows:

- $P_1 = 3.12$, $P_2 = 1.44$, $P_3 = 1.43$, $P_4 = 0.64$, $P_5 = 1.15$, $P_6 = 2.76$, $P_7 = 1.40$, $P_8 = 1.02$, $P_9 = 0.24$, $P_{10} = 0.43$

The summation of $P_1$ to $P_{10}$ is $3.12 + 1.44 + 1.43 + 0.64 + 1.15 + 2.76 + 1.40 + 1.02 + 0.24 + 0.43 = 13.65$

The authors obtained the adjust factor (AF) for bridges, which is 6.192. By adopting Equation (10), the FS for BSB is calculated to be 84.50. Table 10 lists the evaluation results for the BSB.

### Table 9. $W_{ijk}$ for the “ecology” indicator of BSB.

| Ecology                                                                 | Design | Construction | Operation | Demolition |
|-----------------------------------------------------------------------|--------|--------------|-----------|------------|
| Ecological environment investigation, data collection, and impact assessment | 1.16   | 0.55         |           |            |
| Site preservation and indicative trees protection                      | 0.89   | 0.53         | 0.16      |            |
| Ecological environment monitoring                                     | 0.72   | 0.75         | 0.32      |            |
| Selection of low impact construction methods and preservation of biodiversity and animal habitat integrity. Establishment of safety facilities for animals | 1.04   | 0.94         | 0.26      |            |

### Table 10. Evaluation results for the BSB. AF, adjust factor; FS, final score.

| Key Indicators               | Evaluation Items | $P_{ijk} \times W_{ijk}$ | $P_i$ | AF   | FS   |
|------------------------------|------------------|---------------------------|-------|------|------|
| Risk mitigation and reliability | Item 1          | 2.73                      |       |      |      |
|                              | Item 2          | 0.00                      | 0.00  |      |      |
|                              | Item 3          | 0.00                      |       |      |      |
|                              | Item 4          | 0.00                      | 0.00  |      |      |
|                              | Item 5          | 2.65                      | 1.92  | 3.12 |      |
|                              | Item 6          | 2.23                      | 2.17  |      |      |
|                              | Item 7          | 2.59                      | 1.99  | 0.39 |      |
|                              | Item 8          | 2.39                      | 1.29  |      |      |
|                              | Item 9          | 0.00                      | 0.00  |      |      |
|                              | $P_1$           | $P_{2j} \times W_i$       |       |      |      |
|                              | $P_2$           | 3.07                      | 2.84  | 3.22 | 4.03 | 13.65 |
|                              | $P_3$           | 2.31                      | 1.09  |      |      |
|                              | $P_4$           | 1.78                      | 1.05  | 0.00 |      |
|                              | $P_5$           | 1.43                      | 1.49  | 0.00 |      |
|                              | $P_6$           | 2.09                      | 1.88  | 0.51 |      |
|                              | $P_7$           | 2.56                      | 1.23  | 0.00 | 0.00 |
|                              | $P_8$           | 1.44                      | 1.43  | 0.36 | 0.00 |
|                              | $P_9$           | 2.41                      | 0.00  | 0.33 | 1.43 |
|                              | $P_{10}$        | 2.20                      | 1.92  | 0.00 | 0.00 |
|                              | $P_{11}$        | 0.95                      | 0.00  | 0.28 |      |
|                              | $P_{12}$        | 6.192                     |       | 84.50|      |
Table 10. Cont.

| Key Indicators          | Evaluation Items | $P_{ijk} \times W_{ijk}$ | $P_i$ | AF | FS  |
|------------------------|------------------|--------------------------|------|----|-----|
|                        |                  |                          |      |    |     |
| Energy Saving          | Item 1           | 0.00 0.00 0.00           |      |    |     |
|                        | Item 2           | 1.94 0.61 0.00           |      |    |     |
|                        | Item 3           | 0.00 1.20 0.00           |      |    |     |
|                        | Item 4           | 1.37 0.00 0.00           | 0.64 |    |     |
|                        | Item 5           | 0.68 0.00 0.80           |      |    |     |
|                        | Item 6           | 0.69 0.63 0.99           | 0.00 |    |     |
| Waste Reduction        | Item 1           | 1.74 0.85 0.58           |      |    |     |
|                        | Item 2           | 0.00 0.91 0.00           |      |    |     |
|                        | Item 3           | 1.86 1.32 0.00           |      |    |     |
|                        | Item 4           | 0.00 0.00 0.00           | 1.15 |    |     |
|                        | Item 5           | 1.59 1.34 0.00           |      |    |     |
|                        | Item 6           | 1.96 1.41 0.00           | 0.00 |    |     |
| Durability             | Item 1           | 3.03 1.02 2.76           | 6.192| 84.50 |
|                        | Item 2           | 2.87 0.84 1.14           |      |    |     |
|                        | Item 3           | 2.13 1.95 1.20           |      |    |     |
|                        | Item 4           | 2.82 1.32 1.92           |      |    |     |
| Benefit and Function   | Item 1           | 2.21 1.04 1.40           |      |    |     |
|                        | Item 2           | 1.14 0.90 0.00           |      |    |     |
|                        | Item 3           | 2.03 1.31 0.37           |      |    |     |
|                        | Item 4           | 1.70 1.39 0.00           |      |    |     |
|                        | Item 5           | 1.88 0.00 0.41           | 1.40 |    |     |
| Landscape              | Item 1           | 2.46 0.87 0.60           |      |    |     |
|                        | Item 2           | 2.87 1.42 0.67           | 1.02 |    |     |
| Humanities and Culture | Item 1           | 0.00 0.62 0.23           |      |    |     |
|                        | Item 2           | 0.33 0.00 0.37           |      |    |     |
|                        | Item 3           | 1.66 1.16 0.00           | 0.24 |    |     |
| Creativity             | Item 1           | 1.65 0.99 0.00           |      |    |     |
|                        | Item 2           | 1.60 0.43 0.00           |      |    |     |
|                        | Item 3           | 0.84 0.62 0.00           |      |    |     |
|                        | Item 4           | 0.00 0.00 0.00           |      |    |     |

As shown in Table 10, the final score (FS) that Baimi Scenic Bridge (BSB) obtained is 84.50 points. This means that the BSB can be certified as “gold grade” on sustainability achievement, as mentioned in Section 4.2.

6. Conclusions

In this research, the researchers propose an applicable and reliable assessment system to cover most of the “sustainability” issues for the life cycle of infrastructures. Under this motivation, the sustainability assessment system for green civil infrastructures (SASGCI) was established to be an assessment tool for green civil infrastructures, including bridges. By performing face-to-face interviews with 47 experts, the authors gathered the data to determine the weight. The multiple attribute value theory (MAVT) and top two boxes theory (TTBT) were adopted for the analysis of the questionnaire results. The research contains the life cycle for the development of infrastructures, including design, construction, operation and maintenance, and demolition stages. In this study, the authors conclude the weights of ten key indicators for bridges as follows: risk mitigation and reliability: 15.3%, durability: 15.1%, landscape: 11.5%, ecology: 10.6%, benefit and function: 9.7%, environmental protection and carbon emissions reduction: 9.5%, waste reduction: 8.5%, energy-saving: 7.1%, creativity: 7.0%, and humanities and culture reservation: 5.6%. The authors select the Baimi Scenic Bridge (BSB) as the case study to verify the applicability of SASGCI. The evaluation results of the BSB indicate that the SASGCI is a practical and functional tool to determine the sustainability achievement of civil infrastructures.
Author Contributions: Conceptualization, T.-Y.L. and N.N.S.C.; methodology, G.-T.L., P.-H.C., and S.-P.H.; software, T.-Y.L.; validation, P.-H.C.; formal analysis, T.-Y.L. and G.-T.L.; investigation, T.-Y.L.; resources, T.-Y.L.; data curation, T.-Y.L.; writing—original draft preparation, T.-Y.L. and G.-T.L.; writing—review and editing, P.-H.C., N.N.S.C., and S.-P.H.; supervision, P.-H.C., N.N.S.C., and S.-P.H.; project administration, T.-Y.L., P.-H.C., and N.N.S.C.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data, models, and code generated or used during the study appear in the submitted article.

Acknowledgments: The authors would like to express a special appreciation to the 47 participated experts for their professional information provided during the interviews, which have contributed to the central database for the establishment of the sustainability assessment system. In addition, we would like to give a special thanks to Suhua Highway Improvement Office for their instruction and supervision on contractors’ construction work of Suhua Highway Improvement Project. Furthermore, we would like to express special appreciation to New Asia Construction and Development Corporation for their help on this research.

Conflicts of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interest.

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