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Measuring the Sustainability of Construction Projects throughout Their Lifecycle: A Taiwan Lesson

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Abstract: Researchers have proposed many industrial or national sustainability evaluation indicator systems during the past decade, although there has not yet been a project-level sustainability evaluation system for the evaluation and execution monitoring of the sustainability status for a construction project. Without such an evaluation system, it will be difficult for the planners to plan the sustainable project objectives, for the contractors to select the sustainable execution alternatives, and for the facility managers to operate sustainable constructed facilities. To meet the abovementioned requirements, this paper presents an effort conducted in Taiwan to propose a Construction Project Sustainability Assessing System (CPSAS) considering three pillars of sustainability: environmental, social, and economic, based on the theoretical backgrounds from the literature and former successful sustainable projects. The proposed CPSAS comprises four levels: Level 1, 3 main pillars; Level 2, 8 categories; Level 3, 19 sub-categories; and Level 4, 31 indicators. Different selections of indicators for application in different project phases are suggested according to the prioritization via questionnaire surveys. A procedure for sustainable project management with the proposed CPSAS is suggested to the project management team. Finally, three green building projects and two civil infrastructure construction projects of Taiwan were tested to demonstrate the feasibility of the proposed CPSAS. It is concluded that the proposed CPSAS is useful for construction stakeholders to achieve sustainability more effectively during the execution of a construction project.

Keywords: sustainable development; project management; performance indicators; construction; Taiwan

1. Introduction

The construction industry has been labelled a non-sustainable industry due to its high energy consumption and greenhouse gas (GHG) emissions, but low productivity. Statistics show that the building industry consumes 40% of energy and emits almost 40% of CO_2 in the USA and other developed countries [1,2], while wasting 57% (compared to 26% in other industries) of its resource inputs during the production process [3]. Paradoxically, the poor performance offers the construction industry a unique opportunity to play the key role in reducing negative environmental impacts, thereby improving global sustainability [4].

Previous researchers have offered different approaches to improve the sustainability of the construction industry, including green innovation of construction methods [5–7], promotion of green building technologies [8,9], development of warm mix asphalt technology that reduces energy consumption and reduces the emission of greenhouse gases and other hazardous compounds [10–12], reuse waste materials (e.g., burning coal in power plants) to reduce environmental impacts [13,14], and implementation of techniques and initiatives for GHG emission elimination [15,16]. As most of the above-mentioned efforts have focused on improvements derived from the technology or process levels, and affecting only single or multiple activities in a construction project, their improvements or impacts on the overall project were quite limited. On the other hand, some other researchers have established different industrial or national indicator systems to evaluate the sustainability of the construction sector of a country [17–20]. Although such types of sustainability evaluation systems are more comprehensive in assessing the sustainability of the construction industry, they are, however, less useful for developing effective strategies to improve the sustainability of a construction project.

Considering the drawbacks of the above two categories, another category of approach that focuses on the project level has been proposed. Labuschagne and Brent [21,22] have proposed a staged project Life Cycle Management (LCM) framework for evaluating the environmental impacts of a new product during the innovation project lifecycle. Although it focuses only on the environmental impacts of a product, such an evaluation framework provides a promising alternative for sustainability monitoring and the improvement of a construction project.

Based on Labuschagne and Brent's concept, the current research proposes a comprehensive project-wise sustainability evaluation framework for a construction project; it provides the project engineers and managers with a useful tool for evaluating and monitoring the sustainability of construction activities throughout the project lifecycle so that effective strategies for sustainability improvement can be more efficiently identified and planned.

The remainder of the paper is organized as follows: the previous sustainability evaluation systems related to this research are reviewed first, then the methodology of current research is described in details; this is followed by presentation of the proposed CPSAS. The case studies of five real-world construction projects are demonstrated after presenting the proposed CPSAS; this is followed by the suggested procedure for management of sustainable construction projects. Finally, findings of the research are concluded and future directions after this research are recommended.

2. Review of Relevant Sustainability Evaluation Systems

The primary concept of sustainability was first proposed in early 1980s. The term sustainable development' was employed in the report to the United Nations General Assembly (UNGA) by the World Commission on Environment and Development (WCED) [23]. The currently widely adopted three pillars (Economic, Social, and Environmental) of sustainability were promulgated in the early 1990s's [24]. Such a three-pillar framework for the assessment of sustainability was adopted by most current national-level sustainability evaluation systems [17,18,20] discussed previously. In regard to improving the sustainability of construction engineering, especially from the viewpoint of project execution, the relevant works in the literature are reviewed below.

The concept of "sustainable construction" was found in literature of the First International Conference on Sustainable Construction in Tampa, Florida, US in 1994 [25]. Hill and Bowen [25] proposed a detailed list of principles and conceptual framework for attaining sustainable construction in terms of four pillars: social, economic, biophysical (relevant to environmental) and technical perspectives. Fernández-Sánchez and Rodríguez-López [26] proposed a method to identify sustainability indicators for construction project management. In their report, a case application of the proposed method was simulated for the infrastructure projects in Spain, which resulted in a list of 30 macro-indicators for assessing the sustainability of an infrastructure project. The methodology proposed by Fernández-Sánchez and Rodríguez-López is quite general, so it can be applied to other types of construction projects. Two other similar works for the identification of sustainability indicators of construction projects, but using different approaches, were conducted by Shen et al. [27] and Huang and Hsu [20], respectively. Shen et al. [27] collected the feasibility study reports of 87 construction projects from China to identify 34 attributes (indicators) related to the sustainability of four types of construction projects. Huang and Hsu [20] identified 30 sustainability indicators of construction engineering from important research literature and government regulations.

Most of the above works, except for the first one by Hill and Bowen [25], adopted the three-pillar perspective, i.e., environmental, social and economic sustainability of construction project. However, several important issues should be taken into account to develop an appropriate sustainability evaluation system for a construction project, as pointed out by different researchers: (1) a more comprehensive angle of sustainability, including product (i.e., the constructed structures in construction project), process (the management process), organization, key stakeholders (project manager and team members) [28], and economic concerns [29,30]; (2) the number of indicators should be not too many for practical and cost-effective implementation [26]. Several researchers have suggested very similar numbers of indicators that are close to 30 [20,26,27], indicating that an indicator system with around 30 indicators is more practical and cost-effective for project implementation; (3) lifecycle concern: the indicator system should not only emphasize the construction project lifecycle (i.e., feasibility study, planning, procurement, construction, and turnover), but also the facility lifecycle (i.e., operation, maintenance, and demolition) [25,26,28]; and most importantly (4) project focus: the indicators should be relevant to the project operations and tasks for management effectiveness since the construction objectives need to be accomplished via project execution [28].

A general methodology was proposed by Fernández-Sánchez and Rodríguez-López [26] to identify the sustainability indicators in construction project management: (1) Review of documentation; (2) Compilation of information through surveys with project stakeholders; (3) Compilation of information through interviews with domain experts; (4) Brainstorming by the project participants; (5) Comparison with other areas and other existing tools; (6) Analysis by checklists related to similar previous projects; and (7) Using diagramming techniques to show the relationship between the system elements and their causality. The two most adopted approaches for developing such kinds of indicator systems are [28]: (1) documentation and literature review: identifying the candidate indicators by reviewing previous literature and legislation documents; and (2) expert survey: conducting questionnaire or interview surveys, or holding focus group meetings, to collect opinions from different stakeholders to determine which indicators should be included. The current research adopts both of these approaches by reviewing the literature to identify candidate indicators first, and then verifying and refining the candidate indicators by expert judgment, via focus groups, interviews and/or questionnaire surveys.

3. Development of Sustainability Evaluation System for Construction Projects

Based on a literature review [25–28], a research methodology for the current study was planned to identify the relevant sustainability indicators for the evaluation and monitoring of construction projects.

3.1. Research Methodology and Procedure

The research procedure adopted in the current research is depicted in Figure 1; it includes the following steps and methods:

(1) Identifying candidate sustainability indicators (SIs): candidate indicators for sustainability assessment are identified through reviews of scientific–technical references and legislation (e.g., national sustainability white paper, government regulations, etc.), and the sustainable construction project case reports published by government agencies. Chang [17] proposed a national sustainable development evaluation indicator system based on the policies and regulations of the Taiwan government, including 23 social indicators and 59 environmental indicators. In investigating the definitions of the 82 indicators proposed by Chang, 39 indicators are related to the construction industry. Hsu [19] developed a national level sustainability indicator system for the construction industry of Taiwan based on a review of the published scientific and technical references in the relevant literature. Hsu's indicator system is comprised of 29 environmental indicators, 27 social indicators, and 11 economic indicators. Although all of the 67 indicators proposed by Hsu are relevant to construction engineering, most of them are measured from the viewpoint of the government agency rather than that of the project manager.

They need to be redefined to fit the requirement for application in a construction project. Finally, 57 candidate indicators belonging to 20 categories were identified as candidate sustainability indicators (SIs) for further analysis.

(2) Pre-screening and prioritizing preliminary SIs for applicable lifecycle stages through domain expert interviews: semi-structured expert interviews were conducted with five domain experts (including a government officer from the River Management Bureau, an architect with a significant amount of green building design experience, a consultant engineer with ecological construction method design and supervision experience, a professional construction manager from one of the major consulting firm, and a site engineer of a general contractor for a green building project) to determine the applicable stages in a project lifecycle based on the four criteria mentioned previously in the literature review: (1) as comprehensive as possible: applicable to different project types and involving important stakeholders; (2) practical to implement: with an indicator number near 30; (3) lifecycle concern: covering all phases of the project lifecycle; and (4) project focus: should be relevant to project management processes or techniques. The interviews were conducted every week for nearly three months until a consensus was reached. The expert interviews finally concluded that 31 preliminary sustainability indicators out of the 57 initial candidate indicators may be applicable to the eight different project stages: (1) Initialization (I); (2) Design and planning (D&P); (3) Construction (C); (4) Monitoring and control (M&C); (5) Completion and turnover (TO); (6) Operation (O); (7) Maintenance (M); and (8) Demolition (D).

(3) Testing with historical sustainable projects: a checklist analysis method adopted from Rodríguez-López [26] was conducted through 12 historical projects to test whether the required information for the selected 31 preliminary SIs could be acquired from real world projects. The historical sustainable construction projects were collected from two public sources: (1) eight green building cases from Taiwan Green Building Council [31]; (2) four ecological construction project cases from the Public Construction Council [32] (refer to Table 1 for the details of the 12 sustainable cases).

The testing results show that all 31 preliminary SIs identified by expert interviews in Step (2) were found to be applicable at least in four out of the 12 cases. The five preliminary SIs with the least applicable historical sustainable construction projects are: (1) E3c1 (Usage of Vertical Green Planting), 83.3% (10/12) applicable; (2) S1a1 (Improvement of Average Occupation Area), 33.3% (4/12) applicable; (3) S1a2 (Improvement of Infrastructure), 66.7% (8/12) applicable; (4) S1a3 (Certified Green Building), 83.3% (8/12) applicable; and (5) S1b1 (Prevention of Disaster), 41.7% (5/12) applicable. Although these five indicators are not applicable to all cases due to specific project characteristics, they are generally useful for sustainability assessment. As a result, all 31 preliminary SIs are considered applicable for the sustainability assessment of construction projects.

(4) Prioritization of selected preliminary SIs through a questionnaire survey: in order to assess the acceptance of the proposed CPSAS from the industry, a questionnaire survey was conducted with 45 experienced industrial practitioners (with previous participation in at least one sustainable construction project, including the owners, the consultants or designers, the general contractors, the suppliers and sub-contractors) of the published historical sustainable construction projects [31,32]. The questionnaire was designed to assess their agreement with the SIs in the eight stages of a project lifecycle. The statistics on the questionnaire returns are summarized in Table 2. Finally 38 effective responses were received, the overall return rate for the questionnaire survey is 84%. The results of the questionnaire survey are shown in Table 3. The profile information of the respondents including their professional positions and seniority of practical experience is depicted in Figure 2. The inter-rater reliability scores [33] for each group of respondents are listed in the fifth column of Table 2 to show the reliability of the survey results. The percentage statistics of survey results for the questionnaire are provided as the supplementary materials of the paper.

(5) Case study demonstration: two types of construction projects (including three green building projects and two ecological civil infrastructure construction projects) were selected for testing with the established CPSAS to demonstrate its applicability. The applications of CPSAS in sustainable construction project management are also addressed and discussed with the case demonstrations.

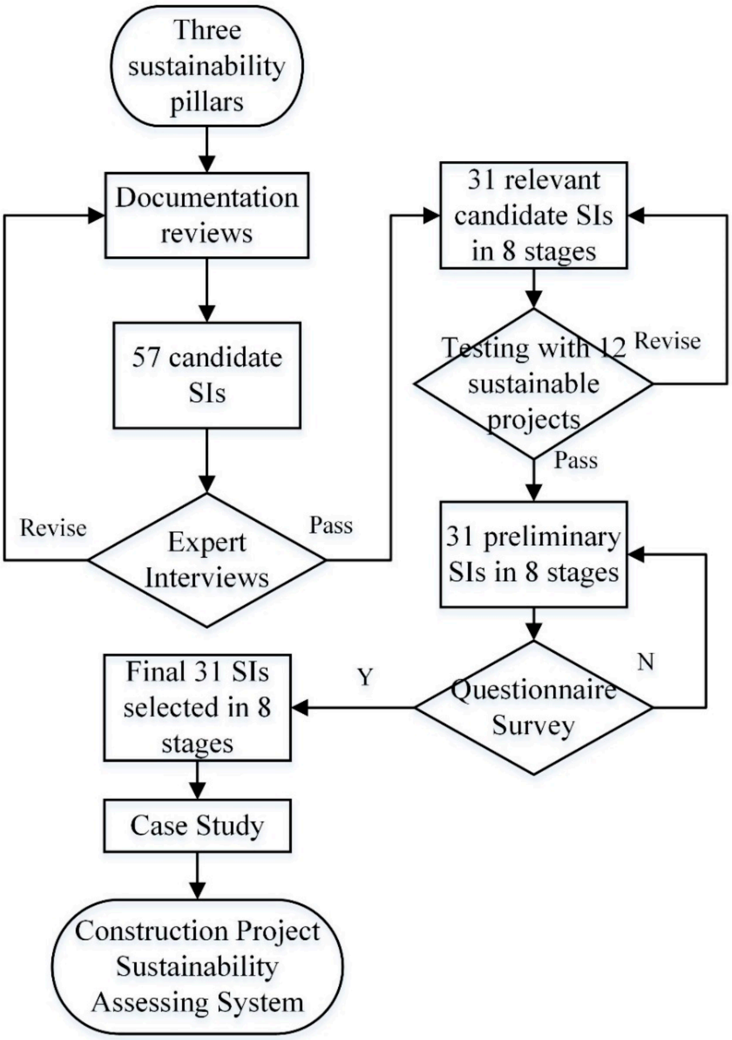

Figure 1. Research procedure. SI: sustainability indicator.

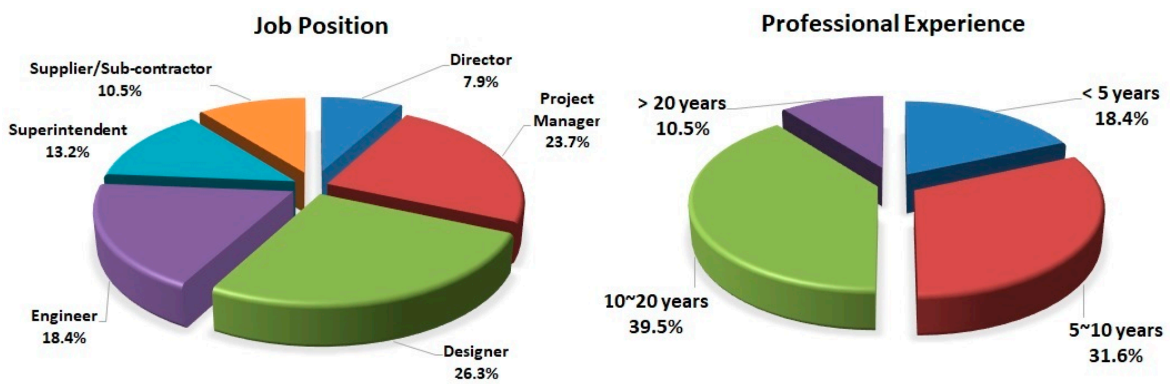

Figure 2. Profile information for the respondents of questionnaire survey.

Table 1. Information on 12 tested sustainable construction projects.

No.	Sustainable Project Type	Project Name	Location	Content of Sustainability	Reference
1	Green building	Soshi High-rise Residential Building Project	Taipei City	EEWH * Certified	[31]
2	Green building	Peitou Library Building	Taipei City	EEWH Diamond Certified	[31]
3	Green building	Delta Electronics, Inc. South Science Park Factory	Tainan City	EEWH Gold Certified	[31]
4	Green building	Neihu Elementary School	Nantou County	EEWH Certified	[31]
5	Green building	Yidzai Elementary School	Tainan County	EEWH Certified	[31]
6	Green building	Residential Hall of ITRI, Liuo-Jia District	Tainan City	EEWH Diamond Certified	[31]
7	Green building	World Game Arena of 2009 in Kaohsiung	Kaohsiung City	EEWH Gold Certified	[31]
8	Green building	Tamsui Sewage Treatment Plat	New Taipei City	EEWH Gold Certified	[32]
9	Ecological method	Tsou-Ten-Ken River renovation project of Taichung County	Taichung City	Green construction method	[32]
10	Ecological method	Lao-Jiey River renovation project of Taoyuan City	Taoyuan City	Green construction method	[32]
11	Ecological method	National Highway No. 6 Construction Project	Nantou County	Energy and carbon emission reduction	[32]
12	Ecological method	The 7-Star Tang Coast Construction Project	Hualien County	Green construction method	[32]

Note: * EEWH is the Green Building Certification System of Taiwan [31].

Table 2. Statistics on the questionnaire distribution and collection.

Domain Experts	No. of Surveys	No. of Valid Returns	%	Inter-Rater Reliability
Owners	15	9	60%	0.230
Architect/Engineer	15	15	100%	0.117
Contractors	15	14	93%	0.214
Overall	45	38	84%	0.180

Table 3. Results of questionnaire survey for the applicability of sustainability indicators in the project lifecycle.

SP *	SC *	Sub-SC *	SI *	Definition of Indicators	Abbr.	Unit	Applicable Project Phases **							
							I	P&D	C	M&C	TO	O	M	D
E	E1	E1a	E1a1	Project Development Area Ratio	DAR	%	92%	100%	32%	29%	21%	16%	0%	0%
		E1b	E1b1	Ratio of Borrowed Soil	RBS	%	16%	82%	68%	32%	0%	0%	8%	0%
			E1b2	Ratio of Concrete Usage	RCU	%	8%	95%	87%	68%	8%	0%	11%	3%
		E1c	E1c1	Measure of Water Saving	MWS	No.	39%	89%	84%	45%	16%	58%	42%	3%
			E1c2	Measure of Water Recycle	MWR	No.	34%	82%	87%	53%	21%	55%	55%	3%
		E1d	E1d1	Measure of Energy Saving	MES	No.	24%	76%	71%	39%	24%	55%	37%	3%
			E1d2	Usage of Green Energy	UGE	Y/N	32%	55%	34%	18%	16%	34%	16%	3%
	E2	E2a	E2a1	Measure of Air Pollution Prevention	APP	No.	16%	45%	76%	32%	13%	55%	42%	13%
			E2a2	Usage of Low Air Pollution Method	LAP	No.	11%	66%	79%	42%	13%	0%	8%	5%
		E2b	E2b1	Measure of Water Pollution Reduction	WPR	No.	21%	66%	79%	45%	18%	42%	13%	37%
		E2c	E2c1	Measure of Solid Waste Reduction	SWR	No.	16%	42%	68%	42%	16%	32%	24%	37%
		E2d	E2d1	Measure of Noise Reduction	MNR	No.	11%	61%	82%	53%	13%	11%	18%	16%
		E2e	E2e1	Alternative for Toxicant	AFT	No.	13%	66%	58%	21%	5%	21%	11%	5%
			E2e2	Usage of Green Labeled Product	GLP	%	21%	87%	79%	50%	24%	37%	21%	3%
		E2f	E2f1	Low GHG Emission Method	LGM	No.	13%	71%	76%	37%	5%	76%	34%	45%
	E3	E3a	E3a1	Ratio of Planting Area	RPA	%	29%	95%	92%	45%	26%	32%	39%	0%
			E3a2	Establishment of Habitation	EOH	Y/N	50%	76%	61%	47%	29%	32%	26%	24%
		E3b	E3b1	Avoid Bio-sensitive Area	ABA	Y/N	55%	63%	42%	34%	24%	24%	18%	18%
			E3b2	Avoid Disaster-sensitive Area	ADA	Y/N	55%	61%	42%	34%	26%	21%	18%	16%
		E3c	E3c1	Usage of Vertical Green Planting	VGP	Y/N	16%	61%	50%	13%	8%	8%	11%	0%
S	S1	S1a	S1a1	Improvement of Average Occupation Area	AOA	Y/N	42%	76%	21%	8%	13%	37%	13%	0%
			S1a2	Improvement of Infrastructure	IOI	Y/N	39%	76%	24%	8%	42%	32%	37%	3%
			S1a3	Certified Green Building	CGB	No.	61%	71%	55%	42%	55%	68%	11%	0%
		S1b	S1b1	Prevention of Disaster	POD	Y/N	61%	71%	68%	29%	21%	24%	18%	5%
			S1b2	Protection of Stakeholders Safety	PSS	Y/N	71%	76%	76%	68%	50%	61%	34%	24%
	S2	S2a	S2a1	Measure of Conserving Cultural Monument	CCM	Y/N	42%	55%	42%	24%	13%	50%	58%	55%
	S3	S3a	S3a1	Free Access for the Disabled	FAD	No.	26%	84%	68%	39%	32%	58%	26%	8%
	S4	S4a	S4a1	Participation of Local Residents	PLR	Y/N	39%	66%	55%	29%	34%	53%	26%	18%
			S4a2	Fair Sharing of Benefits	FSB	Y/N	53%	55%	32%	18%	18%	21%	13%	16%
EC	EC1	EC1a	EC1a1	Ratio of Local Employment	RLE	%	16%	18%	61%	18%	0%	13%	50%	24%
			EC1a2	Self-Liquidation Ratio	SLR	%	55%	84%	11%	24%	11%	71%	8%	0%

* Note: Sustainability Pillars (SP): Environmental (E), Social (S), Economic (EC), Sustainability Categories (SC); Sustainability Sub-Categories (Sub-SC); ** Project Phases: I—Initialization; P&D—Plan and Design; C—Construction; M&C—Monitoring and Control; TO—Turnover; O—Operation; M—Maintenance; D—Demolition.

3.2. Proposed Construction Project Sustainability Assessing System (CPSAS)

The resulting SIs for assessing the sustainability of a construction project, namely the Construction Project Sustainability Assessing System (CPSAS), is illustrated in Figure 3. The framework of CPSAS comprises four levels: (1) Level-1: Sustainability Pillars (SP): 3 pillars of sustainability are defined: environmental sustainability (E), social sustainability (S), and economic sustainability (EC); (2) Level-2: Sustainability Categories (SC): total of 8 sustainability categories belonging to the 3 pillars are defined; (3) Level-3: Sustainability Sub-Categories (Sub-SC): total of 19 sustainability sub-categories are identified for the eight sustainability categories; (4) Level-4: Sustainability Indicators (SI): total of 31 sustainability indicators are identified. The detailed definitions for the 31 SIs are shown in Table 3. Based on the agreement percentage (%) depicted in Table 3, the SIs with different importance suggested to be adopted for different stages of the project lifecycle are shown in Table 4.

With the proposed CPSAS, the overall Project Sustainability Index (*PSI*) can be calculated for a specific construction project. According to CPSAS defined in Table 3 and Figure 3, there are two types of indicators: (1) Quantitative indicators: measured by the percentage (%) of values or quantities (No.) of the indicators; and (2) Non-quantitative indicators: measured by 'Yes or No (Y/N)' of the outcome of the indicators. The two indicator types are aggregated in *PSI* using the following equation:

$$PSI = \frac{\sum_{i=1}^{m} PSI_{nq}(i) + \sum_{j=1}^{n} PSI_{q}(j)}{m+n} \times 100\%, \quad (1)$$

where *PSI* is the Project Sustainability Index in percentage (%); m is the number of qualitative (non-quantitative) indicators; $PSI_{nq}(i)$ is the evaluated result of the ith qualitative indicator; n is the number of quantitative indicators; $PSI_q(j)$ is the evaluated result of the jth qualitative indicator.

Table 4. Suggested SIs for different stages of project lifecycle.

SP	SC	Sub-SC	SI	Abbr.	Applicable Project Phases							
					I	P&D	C	M&C	TO	O	M	D
E	E1	E1a	E1a1	DAR	●	●	○	△	△	△		
		E1b	E1b1	RBS	△	●	◎	○				
			E1b2	RCU		●	●	◎			△	
		E1c	E1c1	MWS	○	●	●	○	△	◎	○	
			E1c2	MWR	○	●	●	◎	△	◎	◎	
		E1d	E1d1	MES	△	●	●	○	△	◎	○	
			E1d2	UGE	○	◎	○	△	△	○	△	
	E2	E2a	E2a1	APP	△	○	●	○	△	○	○	△
			E2a2	LAP	△	◎	●	○	△			
		E2b	E2b1	WPR	△	◎	●	○	△	○	△	○
		E2c	E2c1	SWR	△	○	◎	○	△	○	△	○
		E2d	E2d1	MNR	△	◎	●	◎	△	△	△	△
		E2e	E2e1	AFT	△	◎	◎	△		○	△	
			E2e2	GLP	△	●	●	◎	△	○	△	
		E2f	E2f1	LGM	△	●	●	○		●	○	○
	E3	E3a	E3a1	RPA	△	●	●	○	△	○	○	
			E3a2	EOH	◎	●	◎	○	△	○	△	△
		E3b	E3b1	ABA	◎	◎	○	○	△	△	△	△
			E3b2	ADA	◎	◎	○	○	△	△	△	△
		E3c	E3c1	VGP	△	◎	◎	△			△	

Table 4. *Cont.*

SP	SC	Sub-SC	SI	Abbr.	Applicable Project Phases							
					I	P&D	C	M&C	TO	O	M	D
S	S1	S1a	S1a1	AOA	○	●	△		△	○	△	
			S1a2	IOI	○	●	△	△	○	○	○	
			S1a3	CGB	◎	●	◎	○	◎	◎	△	
		S1b	S1b1	POD	◎	●	◎	△	△	△	△	
			S1b2	PSS	●	●	●	◎	◎	◎	○	△
	S2	S2a	S2a1	CCM	○	◎	○	△	△	◎	◎	◎
	S3	S3a	S3a1	FAD	△	●	◎	○	○	◎	△	
	S4	S4a	S4a1	PLR	○	◎	◎	△	○	◎	△	△
			S4a2	FSB	◎	◎	○	△	△	△	△	△
EC	EC1	EC1a	EC1a1	RLE	△	△	◎	△		△	◎	△
			EC1a2	SLR	◎	○	●	△	△	●		
No. of Relevant SIs					30	31	31	29	25	29	27	13

Note: (1) Legend: ●—Very important; ◎—Important; ○—Medium; △—Minor. (2) Abbreviations refers to Table 3.

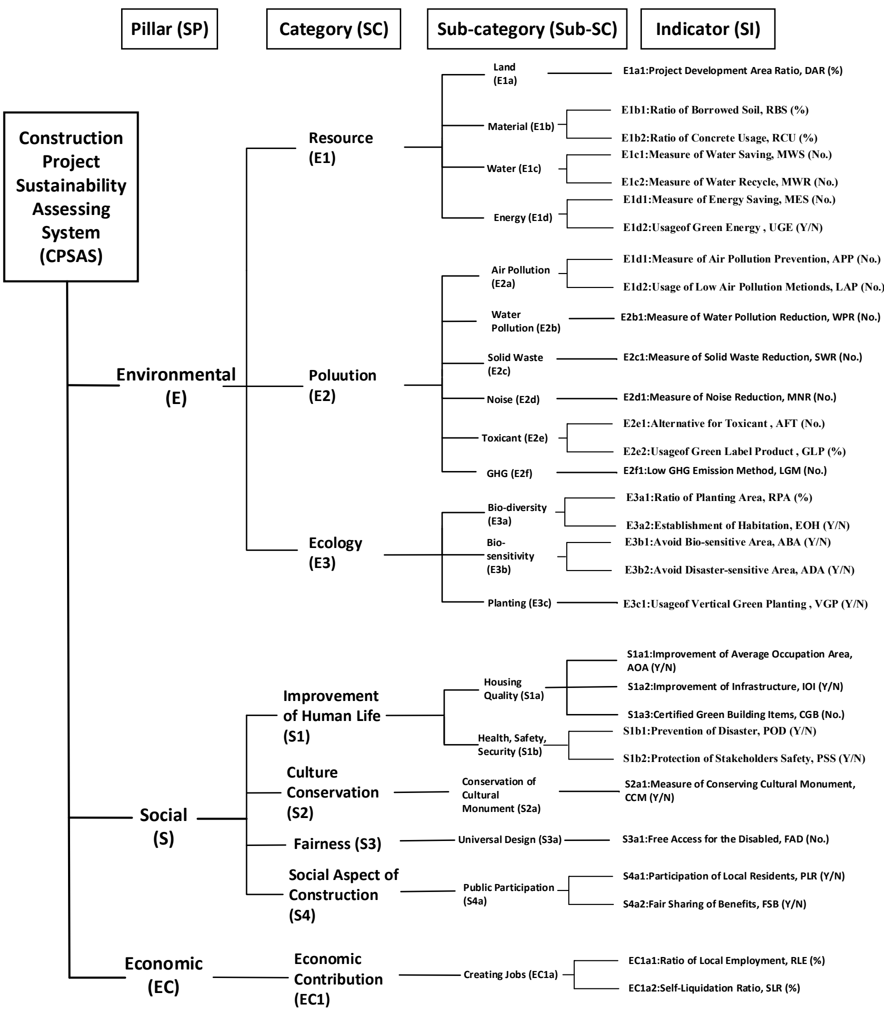

Figure 3. Framework of Construction Project Sustainability Assessing System (CPSAS).

The non-quantitative, $PSI_{nq}(i)$, and quantitative, $PSI_q(j)$, sustainability indicators in Equation (1) are further defined in the following:

- Non-quantitative Sustainability Indicators (PSI_{nq})

In CPSAS, there are 12 indicators of PSI_{nq}. The results of the 12 PSI_{nq} indicators are either 'Pass' (noted as 'Y' in Figure 3) or 'Fail' (noted as 'N' in Figure 3). When an indicator satisfies the defined requirements, it is assessed as 'Y' with the PSI_{nq} value of '1'; otherwise, it is assessed as 'N' with PSI_{nq} value of '0'. For example, 'E1d2—Usage of Green Energy (UGE)' requires the use of any kind of renewable energy (e.g., solar, wind, or co-generation electricity) utilized in the project. If any is in place, it is assessed as 'Y' (PSI_{nq} = 1).

- Quantitative Sustainability Indicators (PSI_q)

There are 19 quantitative indicators of PSI_q in the proposed CPSAS. Among these, 6 are assessed in percentage (%) and 13 are assessed in numbers. Most of the percentage indicators are ratios of two parameters collected from the project; the numeric (No.) indicators are counted in integer numbers. Thresholds are defined for different PSI_q indicators. For example, for 'EC1a1—Ratio of Local Employment (RLE)', the threshold value may be set as 20% to encourage the creation of jobs for the local community by the project contractor. If the RLE is ≥20%, it is assessed as 'Y' (PSI_q = 1); otherwise, it is assessed as 'N' (PSI_q = 0). Similarly, an example of the numeric indicators for 'S1a3—Certified Green Building (CGB)', the threshold value required by the local regulation for the EEWH Green Building Certification System [34] in Taiwan requires at least four quantified items to be certified as 'Green Building'.

Finally, the overall *PSI* of the project is calculated using Equation (1). The Level of Project Sustainability (LPS) in this research is determined arbitrarily using the following rules:

(1) If $PSI < 50\%$, the project is determined as 'Low-Sustainability;
(2) If $50\% \leq PSI < 76\%$, the project is determined as 'Bronze Sustainability;
(3) If $76\% \leq PSI < 86\%$, the project is determined as 'Silver Sustainability';
(4) If $PSI \geq 86\%$, the project is determined as 'Gold Sustainability'.

It is noted that the criteria of LPS provide project stakeholders an overall figure of the project sustainability. It can be altered and tuned more appropriately by the project manager or the project owner after several practical applications of the proposed CPSAS.

3.3. Determining Indicator Criteria

The criteria of the Sustainability Indicators (SIs) in Table 3 will affect the overall Project Sustainability Index (*PSI*) and further determine the Level of Project Sustainability (LPS). As a result, it is very important to select appropriate 'Pass' or 'Fail' criterion for each SI. As discussed previously, some criteria are 'hard' requirements regulated by the local sustainability related regulations, e.g., the 'S1a3—Certified Green Building (CGB)' is regulated by the EEWH Green Building Code of Taiwan [34], the 'E2e2—Usage of Green Labeled Product (GLP)' is regulated by the Public Construction Commission (PCC) of Taiwan [32]. The other criteria are 'soft' requirements that can be determined by the project stakeholders according to their expectations or intentions to achieve the project sustainability. For example, the 'E3a1—Ratio of Planting Area (RPA)' of environmental pillar will improve the biodiversity and living quality in the long term; the 'EC1a1—Ratio of Local Employment (RLE)' of economic pillar will create jobs for local community and will improve social relationship between the facility owner and the local residents in the long term. The criteria of both abovementioned indicators can be set up by the project owner for their long term goals.

4. Demonstrated Case Studies

In this section, five construction projects, including three green building projects and two civil infrastructure construction projects, were selected for testing the proposed CPSAS to demonstrate its applicability.

4.1. Background of Selected Case Projects

The background information on the five selected real world cases are described in Table 5. The sustainability assessments were tested for different project stages according to the information available for each project during the time the research was conducted. Two (Case I and II) projects were assessed for the Plan and Design (P&D) stage; one (Case III) project was assessed for Construction (C) stage; one (Case IV) project was assessed for Turnover (TO) stage; and one (Case V) project was assessed for Operation (O) stage.

Table 5. Suggested SIs for different stages of project lifecycle.

No.	Characteristics	Demonstrated Cases				
		I	II	III	IV	V
1	Project Name	R&D Building of NTHU	High-rise Residential Building	Sang-Hsin Township Hall	Sha-lun Dam Renovation of Da-Han River	National Highway No. 6
2	Location	Hsinchu	New Taipei	Yi-lan	Taichung	Nantou
3	Type	Building	Building	Building	Civil	Civil
4	Area/Length	6435 m^2 (6-story)	52,277 m^2 (32 + 8-story)	2576 m^2 (2-story)	98 m	37.6 km
5	Primary Green Content	EEWH Green Building	EEWH Green Building	EEWH Green Building	Ecological Construction Method	Ecological Construction Method
6	Assessment Stage	Plan and Design	Plan and Design	Construction	Turnover	Operation

4.2. Assessment of Sustainability Indicators

The Sustainability Indicators (SIs) of the proposed CPSAS were assessed according to the definitions of the SIs in Table 3. The first step in assessing the SIs was to determine the criterion of 'Pass' for each indicator in the CPSAS. In the case study, the criteria were mainly determined according to the local regulations. For example, the Public Construction Commission (PCC) of Taiwan requires 'E2e2—Usage of Green Labeled Product (GLP)' to be at least 10% for a sustainable public construction project; thus, the criterion of 'Pass' criterion of E2e2 was '$\geq$10%'. Similarly, the certified green building according EEWH standard requires at least four qualified items, so the 'Pass' criterion for 'S1a3—Certified Green Building (CGB)' was set as '$\geq$4'. The other criteria for the rest indicators are shown in the fifth column of Table 6. The results of the assessment for the SIs of the six demonstrated cases are depicted in Column 6–10 of Table 6. The original values for the numeric indicators (PSI_q) are represented in the parentheses, and the assessed results are shown in front of the parentheses. There are some assessed indicators shown as 'N/A', which means the indicators are not applicable for the case due to the project characteristics. For example, the 'S1a1—Improvement of Average Occupation Area (AOA)' and 'S1a3—Certified Green Building (CGB)' are not applicable for the river renovation project type of Case IV and the highway project type of Case V. Similarly, the 'S2a1—Measure of Conserving Cultural Monument (CCM)' and the 'S4a2—Fair Sharing of Benefits (FSB)' are not applicable for the river renovation project type of Case IV. All applicable indicators were assessed and given resultant values in Table 6.

Table 6. Results of SI assessment for the five demonstrated cases.

SP	SC	Sub-SC	SI	Criterion	Demonstrated Cases				
					I	II	III	IV	V
E	E1	E1a	E1a1	≥60%	Y(100%)	Y(80%)	N(20%)	Y(93%)	Y(100%)
		E1b	E1b1	≤50%	Y(0%)	Y(0%)	Y(0%)	-	-
			E1b2	≤40%	Y(40%)	Y(20%)	Y(20%)	-	-
		E1c	E1c1	≥1	Y(3)	Y(2)	Y(2)	N/A	Y(0)
			E1c2	≥1	Y(1)	Y(1)	Y(1)	N/A	N(0)
		E1d	E1d1	≥1	Y(4)	Y(4)	Y(3)	Y(2)	Y(1)
			E1d2	Y/N	Y	N	Y	Y	Y
	E2	E2a	E2a1	≥1	Y(1)	Y(1)	Y(1)	Y(1)	Y(2)
			E2a2	≥1	N(0)	N(0)	N(0)	Y(1)	-
		E2b	E2b1	≥1	Y(1)	Y(1)	Y(1)	N(0)	N(0)
		E2c	E2c1	≥1	Y(1)	Y(1)	Y(1)	Y(1)	Y(1)
		E2d	E2d1	≥1	N(0)	N(0)	N(0)	N(0)	Y(1)
		E2e	E2e1	≥1	Y(1)	Y(1)	Y(2)	-	Y(2)
			E2e2	≥10%	Y(60%)	Y(80%)	Y(70%)	Y(14%)	Y(70%)
		E2f	E2f1	≥1	Y(2)	Y(1)	Y(1)	-	Y(2)
	E3	E3a	E3a1	≥40%	N(30%)	Y(60%)	Y(20%)	N(35%)	Y(85%)
			E3a2	Y/N	Y	Y	Y	Y	Y
		E3b	E3b1	Y/N	Y	Y	Y	Y	Y
			E3b2	Y/N	Y	Y	Y	Y	Y
		E3c	E3c1	Y/N	N	Y	Y	-	-
S	S1	S1a	S1a1	Y/N	Y	Y	Y	N/A	N/A
			S1a2	Y/N	Y	Y	Y	Y	Y
			S1a3	≥4	Y(8)	Y(6)	Y(6)	N/A	N/A
		S1b	S1b1	Y/N	Y	Y	Y	Y	Y
			S1b2	Y/N	Y	Y	Y	Y	Y
	S2	S2a	S2a1	Y/N	N	Y	N	N/A	Y
	S3	S3a	S3a1	≥1	Y(3)	Y(3)	Y(3)	N/A	N/A
	S4	S4a	S4a1	Y/N	N	Y	Y	Y	Y
			S4a2	Y/N	N	Y	N	N/A	Y
EC	EC1	EC1a	EC1a1	≥20%	Y(40%)	Y(50%)	Y(60%)	-	Y(60%)
			EC1a2	≥50%	N(30%)	Y(100%)	N(0%)	N(0%)	Y(50%)

Note: (1) Legend: 'Y'—Pass the pre-defined criterion; 'N'—Fail to pass the criterion. (2) Abbreviations refers to Table 3.

4.3. Project Sustainability Index (PSI) Calculation

The *PSI* for each demonstrated case was calculated according to Equation (1). The calculation results are summarized in Table 7. It is noted from Table 7 that the overall project *PSI*s range from 71% to 92%. Case I is ranked as 'Bronze' level; Cases III and IV are ranked as 'Silver' level; and Cases II and V are both ranked 'Gold' level for their sustainability.

Table 7. Overall Project Sustainability Index (*PSI*) for demonstrated case projects.

Demonstrated Case	I	II	III	IV	V
No. of Relevant Sustainability Indicators	31	31	31	25	29
No. of indicators applicable	31	31	31	19	26
No. of 'Pass' indicators	23	28	25	15	24
Overall Project *PSI*	74.2%	90.3%	80.6%	78.9%	92.3%
Sustainability Rank	Bronze	Gold	Silver	Silver	Gold

4.4. Suggested Procedure for Sustainable Project Management

The proposed CPSAS not only provides an overall *PSI*, as shown in Table 6, but also provides the direction for improving the sustainability for project management. For example, Case I is assessed as the least sustainable project among the five demonstrated cases. From Table 5, it is noted that many SIs are poor in sustainability performance, e.g., 'E2a2—Usage of Low Air Pollution Method (LAP)', 'E2d1—Measure of Noise Reduction (MNR)', 'E3a1—Ratio of Planting Area (RPA)', 'E3c1—Usage of Vertical Green Planting (VGP)', and 'S4a2—Fair Sharing of Benefits (FSB)'. Most of these indicators can be improved during the 'Plan & Design' stage (when the assessment takes place). Thus, the project team is guided to plan the actions for sustainability improvement.

Nevertheless, the proposed CPSAS provides the project management team with a suggested list of assessment indicators for monitoring the project sustainability during each stage of a project lifecycle. Such project management initiatives can be triggered by a 'Stage-gate' procedure, as suggested in Figure 4.

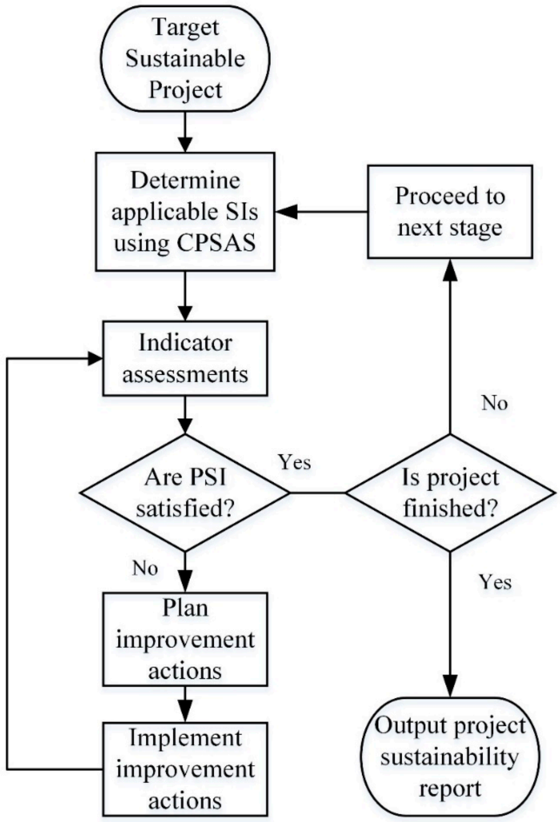

Figure 4. Suggested management procedure for attaining sustainable project with the proposed CPSAS.

In the procedure of Figure 4, the 'Stage-gate' is set at the end of each project stage, where the *PSI* for the stage is assessed by the project management team. If the *PSI* is not satisfied, improvement actions should be planned and implemented according to the SI assessment results obtained from

CPSAS; otherwise, the project is allowed to proceed to the next stage. Finally, the project sustainability performance report can be generated as a lesson learned for future projects at the end of the project.

5. Conclusions and Recommendation

The construction industry has been criticized as a non-sustainable industry due to its low productivity but high resource consumption. However, there has not yet been an effective tool to monitor and achieve the expected sustainability for construction projects from stakeholders' viewpoints. In this paper, a Construction Project Sustainability Assessing System (namely CPSAS) is proposed to provide the engineers and the manager with a tool to monitor and control the process sustainability of a construction project. The proposed CPSAS comprises four levels: Level 1, 3 main pillars; Level 2, 8 categories; Level 3, 19 sub-categories; and Level 4, 31 indicators. Five demonstrated cases, including three building projects and two civil construction projects, were selected to test the feasibility of the proposed CPSAS. A procedure for sustainable project management with the proposed CPSAS is also suggested to the project management team.

Although the study was conducted through surveys based on the literature, historical sustainable construction projects and the domain experts in Taiwan, the proposed model can be tailored to fit the need of sustainability in the other countries or areas. Table 4 offers the project management team the selection set of sustainability indicators to meet requirements of different project phases. Table 6 provides the project stakeholders with a tool to set up thresholds of sustainability indicators that determine the levels of sustainability expected by different project participants. Finally, Figure 4 is offered as a guide for the implementation of sustainable construction project management. The project stakeholders (especially, the project owners and managers) have to determine the thresholds for the 'Pass or Fail' criteria according to their expectations and requirements on project sustainability. Moreover, the Level of Project Sustainability (LPS), which provides a compass to monitor the overall project sustainability should be adjusted with more experiences collected from practical implementations. With such a tool, the project management team is better equipped to achieve a more sustainable construction project. It is concluded that the proposed CPSAS is useful for construction stakeholders to effectively monitor the sustainability of the construction activities during the project lifecycle so that the project team is able to plan strategies to manage the project in order to achieve effective construction sustainability.

The proposed CPSAS has been tested with five sustainable projects; however, more and different types of sustainable projects need to be considered for comprehensive verification. The research team plans to implement the proposed CPSAS in a land development project located in Hsinchu City in North Taiwan. Other specialized construction projects also need to be tested, such as industrial construction projects, ocean construction projects, etc.

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