Key Assessment Indicators for the Sustainability of Infrastructure Projects

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Abstract: Infrastructure projects have major effects on implementing the principles of sustainable development. Infrastructure projects will continue to be developed in the coming years, particularly in developing countries such as China and India; therefore, it is important to find methods and solutions for improving the sustainability of them. Although existing studies have suggested various methods for practicing sustainable development principles in the process of implementing infrastructure projects, effective assessment indicators are unavailable, which presents a barrier to the effective assessment of infrastructure project sustainability. This study introduces key assessment indicators (KAIs) for assessing the sustainability performance of an infrastructure project. The research data used for analysis were collected from a questionnaire survey given to three groups of experts, including government officials, professionals, and clients in the Chinese construction industry. The fuzzy set theory was used to establish KAIs. A procedure for using the KAIs is demonstrated by a case study. These research findings provide an alternative solution to appraise the sustainability of infrastructure projects. **DOI: 10.1061/(ASCE)CO.1943-7862.0000315.**

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Introduction

An infrastructure project is a kind of public good in which government policy has an important role to influence the effects of the project on economic development and social needs. The term *infrastructure* covers a range of services, from public utilities such as power, telecommunications, water supply, sanitation and sewerage, solid waste collection and disposal, and piped gas; to public works such as roads, dam and canal works, railways, urban transport, ports and waterways, and airports (World Bank 1994). Infrastructure is the foundation for social and economic development; thus, investments in infrastructure are particularly important in developing countries. From 1970 to 2005, more than 30% of the World Bank's investments were in developing countries for implementing various infrastructure projects (World Bank 2006). The promotion of infrastructure projects has been making significant contributions to the development of developing countries. In China, for example, the investment in power plants in the last two decades has led to the increase of power-generating capacity to 718 million kilowatts in 2007, which was 11.6 times of that in 1978 [Central People's Government of the People's Republic of China (CPGC) 2008a]. Investments in infrastructure are also an important means to stimulate economic activities. For example, the Chinese government recently planned to invest more than RMB$2,000 billion in various infrastructure projects to stimulate the national economy, which has suffered from the world financial crisis by the end of 2008. These infrastructure projects include railway, road, airport, electrical power, and infrastructure projects for rural areas for the years 2009 and 2010 (CPGC 2008b).

The value of an investment in infrastructure can only be realized if the investment is well planned and implemented properly. Nevertheless, it is often reported that inefficient, ineffective, and even wasted infrastructure investments occur. For example, according to an early survey by World Bank (1994), on average, 40% of the power-generating capacity in developing countries was not used. A recent report by the World Bank (2005) suggests that many infrastructure projects, such as harbor and railways in Latin American and the Caribbean region, have not been effectively used. Some large investments in road construction in Africa are abandoned for insufficient maintenance. It appears that many governments across the world have been spending more on new infrastructure and less on infrastructure maintenance. In China, for example, reports are often heard about a gas pipe leak or explosion, a bridge collapse, or piped water pollution [Editorial Committee of China Urban Development (ECCUD) 2008]. These accidents occurred because of the insufficient maintenance of infrastructure. The operation of poorly maintained infrastructure projects has induced various social and environmental problems. For example, it was reported by Bian (2003) that the burst of water pipes is not unusual in cities such as Beijing, resulting flooded streets and water shut-off to residents. Great numbers of dams cross rivers in China for the purposes of irrigation and electricity generation, but a significant number of dam projects have caused serious environmental problems and ecological disasters.

The consequences from investments in infrastructure often present more economical benefits but do cause certain negative

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effects, particularly for social and environmental dimensions. Problems identified in existing studies have cast doubt on the effectiveness and adequacy of the assessment of infrastructure investment. Assessments need to be improved by incorporating the attributes embodied in sustainable development principles, which is widely described as a triple bottom line (i.e., economic, social or organizational, and environmental) (Griffith and Bhutto 2008).

In line with the promotion of the principle of sustainable development, infrastructure projects should be developed to bring benefits across all aspects, including economic, social, and environmental. Considering that the effects of infrastructure construction activities on the environment are more significant than from other industries [International Council for Research and Innovation in Building and Construction (CIB) 1998], more efforts for protecting the environment have been developed in recent years for the implementation of an infrastructure project. However, environmental and social effects of infrastructure projects usually are not assessed properly in the project's feasibility study; they often are identified during or after the implementation of the project (World Bank 2006).

Several studies have analyzed infrastructure project sustainability from different perspectives. For example, Choguill (1996) proposed principles for policy formulation to improve infrastructure sustainability through serving and cooperating with communities in the processes of project planning, decision making, and implementation. Rackwitz et al. (2005) introduced a maintenance strategy for improving infrastructure effectiveness on the basis of cost-benefit analyses focusing on project performance during the operation stage. Ugwu and Haupt (2007) proposed an indicator system for assessing infrastructure sustainability focusing on the project operation stage. Other studies have investigated the methods for strategic environmental assessment (SEA) for infrastructure projects (Arce and Gullon 2000; Bobylev 2006). Colorni et al. (1999) introduced a method to assess the environmental effect of transportation infrastructure by using a decision support system. Shen et al. (2005) developed a prototype model for assessing the sustainability of construction projects across their life cycles by using a system dynamic method. Other studies contributed to the examination of sustainability for different types of infrastructure, such as transportation, wastewater, and energy (Timmermans and Beroggi 2000; Lundin and Morrison 2002; Sahely et al. 2005; Brown and Sovacool 2007; Ugwu and Haupt 2007; Klevas et al. 2009).

The findings on sustainability indicators for infrastructure projects from previous studies are summarized in Table 1. The indicators adopted in these previous studies for project sustainability assessment are fragmental, and no method incorporates the three dimensions embodied in sustainable development principles (i.e., economic, environmental, and social). Therefore, the applications of previous methods for assessing project sustainability are limited. This has motivated the writers of this paper to undertake a study to formulate a list of key assessment indicators (KAIs) that integrate the three dimensions of sustainability for guiding the assessment for the sustainability performance of infrastructure projects before their implementation.

Research Method

To identify assessment indicators, the writers examined a set of feasibility reports for infrastructure projects and referred to previous

Table 1. Sustainability Assessment Indicators in Previous Studies

Selected sustainability indicators in previous studies	Related literature	Perspectives
Economic sustainability, social sustainability, technological safety, attractiveness for living, attractiveness for businesses	Timmermans and Beroggi 2000	Planning of infrastructure projects
Annual freshwater withdrawal/annual available volume, water use per capita per day, water treatment projects' performance, chemical use for drinking and waste water treatment	Lundin and Morrison 2002	Urban water infrastructure projects
Minimal technical requirements of the solution projects; costs of investment, operation, and maintenance; optimal resource utilization; institutional requirements and acceptance	Balkema et al. 2002	Wastewater infrastructure projects
SO_2 and CO_2 emissions per capita and per GWh, electricity system performance indices, distribution of electricity consumption figures across the population, total electricity consumption per GDP and per capita, electricity portfolio, transmission and distribution losses	Rosenthal 2004	Electricity infrastructure projects
Construction materials usage; energy and water usage; capital, operation, and maintenance costs; expenditures in research and development change; performance in building function; accessibility; health and safety acceptability	Sahely et al. 2005	Buildings, transportation, and water supply infrastructure projects
Economic efficiency, length of railway and main roads, passenger kilometers, CO_2 emissions, per-capita use of transportation energy, death injuries, accidents, residential population exposed to outside road traffic noise	Jeon and Amekudzi 2005	Transport infrastructure projects
Electricity reliability, oil security, energy efficiency, environmental quality	Brown and Sovacool 2007	Energy policy in infrastructure projects
Initial cost, life-cycle cost, extent of land acquisition, extent of loss of habitat or feeding grounds, extent of encroachment on concerned areas, complaints from local parties/villages	Ugwu and Haupt 2007	Civil engineering infrastructure projects
Growth in GDP; effect on environment expressed in external costs; effect on job market, equity, technological innovation, and security of energy supply	Klevas et al. 2009	Energy infrastructure projects

research work. A content analysis method was used for conducting the examination. Content analysis is one of the classical approaches used to study research problems from documentary evidence (Holsti 1969). The method is considered effective and has been widely used in social science (Rattleff 2007). The adoption of the content analysis method in this study led to the generation of a list of optional indicators for assessing infrastructure project sustainability. These optional indicators are divided into three groups, including economical, social, and environmental factors.

From the formulation of the optional indicators for assessing infrastructure project sustainability, a questionnaire survey was conducted to collect data from various groups of experts for analyzing the significance of each assessment indicator. Experts were invited to indicate the significance of each indicator by using a five-point Likert scale. The responses from experts enabled the calculation of indicator significance, and consequently, all indicators were ranked by significance in each factor group.

Furthermore, both the reliability and the validity of the survey data were checked. The tests for reliability and validity are important because they become the basis for data analysis. The adequacy of the information depends on the reliability of the data collected from the questionnaire survey. The assessment indicators included in the questionnaire survey were grouped in three categories: economical, social, and environmental. The reliability of the classification must be checked, and only reliable classification can provide consistent responses. In general, reliability is estimated by examining the consistency with which different items express the same concept (de Vaus 2002). In this study, the Cronbach's alpha coefficient method was used to test the reliability of the group classification for assessment indicators. A previous study suggested that a value of Cronbach's alpha of 0.7 or higher normally indicates a reliable group classification set (Ceng and Huang 2005).

From reliable and valid data, a model was designed to identify KAIs. The model involves uncertainties and fuzzy variables; thus, fuzzy set theory was used in the application of the model. Finally, a procedure is recommended for using the KAIs in the assessment of infrastructure project sustainability.

Option List of Assessment Indicators

In the process of pursuing this research, 23 completed and effective feasibility reports of various types of infrastructure projects were collected from the Chinese construction industry: eight from Chongqing, six from Hangzhou, three from Beijing, three from Shanghai, and three from Shenzhen. Detailed information from these reports is provided in Table 2. Three types of sources, including government officials, professionals, and clients, provided these feasibility reports. In this study, the client refers to state-owned organizations, which is different than a government official. In fact, the research team collected 35 reports, but 12 of them were very brief and incomplete. Thus, only the 23 were studied for analysis. From the content analysis conducted on these feasibility reports, indicators occurring more than five times were selected. References were also given to previous studies. Consequently, a list of 30 assessment indicators was formulated, as shown in Table 3.

Table 2. Details of Feasibility Study Reports Collected in Study

Number	Name of project	Location[a]	Project size	Project cost (RBM$Million)	Operation capacity	Sources[b]
1	Light rail transit (Line 2)	CQ	9.15 km	4,300	18 stations	G
2	Yingbin Bridge	CQ	6.07 km	2,500	6 lanes, 80 km/h	G
3	Wanda Piazza	CQ	780,000 m^2	4,000	Subcenter of city	P
4	Zhongliang hydropower	CQ	9,859 m^3	9,400	122 MW	P
5	Panlong Street	CQ	14 km	217	6 lanes, 40 km/h	P
6	Chongqing-lichuang Railway	CQ	264 km	27,000	12 stations, 200 km/h	P
7	Beifu-jiangjin freeway	CQ	99 km	5,100	6 lanes, 100 ~ 120 km/h	P
8	Shizhu power plant	CQ	2,700 MWh	2,740	2 × 350 MW	C
9	Metro project (Line 1)	HZ	48 km	22,000	30 stations	P
10	Qingchun Tunnel	HZ	5.35 km	1,950	4 lanes, 60 km/h	G
11	Qiubao Bridge	HZ	2.04 km	1,900	6 lanes, 80 km/h	C
12	BRT Line 1	HZ	28 km	150	25 stations	P
13	Hangzhou-ningbo Railway	HZ	152 km	21,800	300 km/h	P
14	Qige sewage treatment plant III	HZ	0.38 km^2	1,641	600 km^3/day	G
15	Metro project (Line 4)	BJ	28.65 km	15,300	24 stations	G
16	Sangyuan Road East renovation	BJ	3.7 km	4	To be convenient for communities	P
17	Underground development of Olympic Park Center	BJ	208,100 m^2	2,050	Public parking and traffic-free street	C
18	Metro project (Section II of Line 2)	SH	6.75 km	3,600	6 stations	P
19	Third Songpu Bridge	SH	1.65 km	150	4 lanes, 80 km/h	C
20	Bailonggang sewage treatment plant renovation	SH	1.2 km^2	2,200	2,000 km^3/day	G
21	Metro project (Section II of Line 1)	SZ	23.95 km	12,100	15 stations	P
22	Flood protection embankment	SZ	3.3 km	120	To resist Level 12 typhoon	G
23	Luosha Road renovation	SZ	4.18 km	300	6 to 10 lanes, 60 km/h	C

[a]CQ = Chongqing; HZ = Hangzhou; BJ = Beijing; SH = Shanghai; SZ = Shenzhen.
[b]G = government official; P = professional; C = client.

Table 3. Option List of Assessment Indicators for Infrastructure Project Sustainability

Group	Indicator	Code
Economical aspect	Analysis of market supply and demand	x_1
	Technical advantage	x_2
	Project budget	x_3
	Project financing channels	x_4
	Project investment planning	x_5
	Life-cycle cost	x_6
	Life-cycle benefit/profit	x_7
	Financial risk	x_8
	Payback period	x_9
	Internal return ratio (IRR)	x_{10}
Social aspect	Effects on local development	x_{11}
	Provision of employment opportunities	x_{12}
	Project function	x_{13}
	Scale of serviceability	x_{14}
	Provision of ancillary amenities to local economic activities	x_{15}
	Public safety	x_{16}
	Public sanitation	x_{17}
	Land use and its influence on the public	x_{18}
	Protection to culture heritage	x_{19}
	Promotion of community development	x_{20}
Environmental aspect	Ecological effect	x_{21}
	Effect on land pollution	x_{22}
	Effect on air quality	x_{23}
	Effect on water quality	x_{24}
	Noise effect	x_{25}
	Waste generation	x_{26}
	Influence on public health	x_{27}
	Environment protection measures in project design	x_{28}
	Energy savings	x_{29}
	Protection to landscape and historical sites	x_{30}

Data Collection and Analysis

Data for analyzing the significance of the assessment indicators listed in Table 3 were collected through a questionnaire survey. The adequacy and readability of the questionnaire was tested with a pilot study. Five experts were involved in the pilot study, and their comments were incorporated into the final questionnaire. In responding to the questionnaire, respondents were invited to indicate the level of significance of each assessment indicator for addressing project sustainability by assigning a score between 1 and 9. A score of "9" indicated most important, "7" important, "5" average, "3" unimportant, and "1" negligible. The scores "8," "6," "4," and "2" represented intermediate judgments between two adjacent judgments.

For the questionnaire survey, 100 candidate respondents were selected from those who participated in the 23 feasibility reports, including government officials, professionals, and clients. As the candidate respondents had knowledge of the research concerns in the process of providing these feasibility reports, the responses were of good quality, and a high response rate was ensured. In total, 95 valid questionnaires were received, 32 from government officials, 44 from professionals, and 19 from clients.

By using the survey data, statistical calculations on the significance of assessment indicators were conducted. The calculation results are illustrated in Table 4. In the table, for example, x_1 represents the indicator "analysis on the market supply and demand" with an overall average score of 7.60 and a standard deviation (SD) of 1.23. However, different response groups gave different scores for individual indicators. For example, according to government officials, x_1 has an average score of 7.19 and a standard deviation of 1.20, whereas according to clients, its average score is 8.32 with a standard deviation of 0.95. This demonstrates that different groups of experts allocate different weighted values to individual indicators. This is appreciated because different groups of experts have different perceptions about the priorities in assessing project sustainability.

Reliability Aanalysis

As stated in the "Research Method" section, the Cronhach's alpha coefficient method was used in this study to test the data reliability. Calculations for Cronbach's alpha coefficients were derived for three factor groups; namely, economical, social, and environmental, from the information provided by the 95 valid respondents. The calculation results are shown in Table 5. The Cronbach's alpha coefficients for all indicators across the three groups are more than 0.7. Therefore, the information from the questionnaires survey is considered reliable.

Analysis of KAIs with Fuzzy Set Theory

The data used for studying KAIs were from a questionnaire survey to three groups of experts. Nevertheless, experts' opinions are subjective and involve fuzziness. Fuzzy set theory was applied to assist in identifying the KAIs. Since Zadeh (1965) introduced fuzzy set theory, it has been applied widely in many disciplines, including science, engineering, agriculture, medicine, and social science.

The symbol $\tilde{A}$ was used to represent a set of KAIs, noted as a KAI set. This KAI set is designed as a fuzzy set:

$$\tilde{A} = \mu_{\tilde{A}}(x_0)/x_0 + \mu_{\tilde{A}}(x_1)/x_1 + \cdots = \sum_{i=0}^{n} \mu_{\tilde{A}}(x_i)/x_i \qquad (1)$$

where x_i = indicator listed in Table 3; n = number of indicators, which is 30, according to Table 3; $\mu_{\tilde{A}}(x_i)$ = degree of membership of x_i in the fuzzy set $\tilde{A}$ and $\mu_{\tilde{A}}(x_i) \in [0, 1]$. Particularly, in Eq. (1), "+" and "/" don't stand for "plus" and "divided by," respectively. They are the symbols of the fuzzy set (Zimmermann 2001). $\mu_{\tilde{A}}(x_i)/x_i$ means that the degree of membership of x_i in $\tilde{A}$ is $\mu_{\tilde{A}}(x_i)$; "+" can be read as "and."

The significance of a particular indicator is scored between 1 and 9, with a score of 5 as a neutral level that is used for differentiating important and unimportant. Therefore, it is reasonable to consider that, if the mean of an indicator's score is less than 5, the possibility for the indictor to be one of the KAI set is less than 50%. Moreover, the value of the SD needs to be incorporated when determining whether an indictor belongs to the KAI set. The larger the SD, the less significant the concerned indicator. Therefore, a parameter Z can be introduced to calculate a value for determining whether an indicator should be included in KAI set:

$$Z = (\text{Mean-5})/SD \qquad (2)$$

Considering that the distribution of an indicator's score allocated by all respondents is in a normal distribution, an 84% probability exists that individual scores from a respondent falls within the range mean-$Z^*SD = 5$; ∞ when $Z = 1$. And a 95% probability exists that the scores fall within the range

Table 4. Significance Score of Individual Assessment Indicators

Group of factor	Indicator code	All ($N = 95$)		Government officials ($N = 32$)		Professionals ($N = 44$)		Clients ($N = 19$)	
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Economical aspect	x_1	7.60	1.23	7.19	1.20	7.59	1.24	8.32	0.95
	x_2	6.52	1.38	6.59	1.13	6.27	1.50	6.95	1.39
	x_3	7.09	1.54	7.06	1.41	7.14	1.30	7.05	2.22
	x_4	6.45	1.82	6.53	1.72	6.11	1.69	7.11	2.16
	x_5	6.23	1.77	6.53	1.68	5.80	1.66	6.74	1.97
	x_6	6.56	1.40	6.84	1.37	6.11	1.30	7.11	1.41
	x_7	6.71	1.82	6.81	1.91	6.34	1.92	7.37	1.21
	x_8	6.80	1.69	6.69	1.86	6.52	1.66	7.63	1.16
	x_9	6.14	1.67	6.22	1.88	5.75	1.45	6.89	1.59
	x_{10}	6.48	1.89	6.09	1.84	6.34	1.95	7.47	1.54
Social aspect	x_{11}	6.93	1.66	6.88	1.66	7.27	1.48	6.21	1.90
	x_{12}	5.57	1.83	5.38	1.77	5.95	1.89	5.00	1.63
	x_{13}	5.79	1.85	5.91	1.84	6.00	1.68	5.11	2.16
	x_{14}	6.49	1.72	6.88	1.52	6.52	1.52	5.79	2.27
	x_{15}	6.08	1.62	6.66	1.52	5.75	1.64	5.89	1.52
	x_{16}	7.09	1.75	7.59	1.54	6.86	1.80	6.79	1.87
	x_{17}	6.44	1.71	6.69	1.64	6.48	1.70	5.95	1.84
	x_{18}	6.09	1.56	6.50	1.55	5.91	1.68	5.84	1.21
	x_{19}	5.74	1.66	6.00	1.50	5.82	1.73	5.11	1.70
	x_{20}	5.56	1.88	5.56	1.97	5.59	1.73	5.47	2.17
Environmental aspect	x_{21}	7.00	1.62	7.25	1.50	6.95	1.64	6.68	1.77
	x_{22}	6.98	1.77	7.41	1.46	6.89	1.82	6.47	2.06
	x_{23}	6.82	1.52	7.03	1.45	6.75	1.62	6.63	1.46
	x_{24}	7.11	1.59	7.31	1.33	7.09	1.67	6.79	1.84
	x_{25}	5.60	1.42	5.91	1.23	5.45	1.49	5.42	1.57
	x_{26}	5.72	1.57	6.03	1.43	5.50	1.55	5.68	1.83
	x_{27}	6.36	1.83	6.84	1.55	6.48	1.91	5.26	1.69
	x_{28}	6.45	1.57	6.72	1.42	6.09	1.60	6.84	1.64
	x_{29}	6.27	1.55	6.53	1.32	6.20	1.56	6.00	1.86
	x_{30}	5.60	1.79	5.72	1.53	6.00	1.48	4.47	2.37

mean-$Z^*SD = 5$; ∞ when $Z = 1.65$. These results are highlighted graphically in Fig. 1.

Nevertheless, the scoring result from the questionnaire survey usually is not in a normal distribution because of the fuzziness involved in the subjective judgment process engaged in by individual respondents. Therefore, instead of adopting a normal distribution, a fuzzy distribution was adopted. On the basis of fuzzy set theory, the possibility for a variable to belong to a group is the degree of membership of the variable in the fuzzy set (Zimmermann 2001). As a result, the degree of membership, $\mu_{\tilde{A}}(x_i)$, can be described as follows:

$$\mu_{\tilde{A}}(x_i) = \int_5^{\infty} f(S_{x_i})dx = 1\text{-}P_f \tag{3}$$

Table 5. Cronbach's Alpha of Data

Economical aspect indicator				Social aspect indicator				Environmental aspect indicator			
Cronbach alpha = 0.798				Cronbach alpha = 0.843				Cronbach alpha = 0.896			
Code	Mean if deleted	Standard deviation if deleted	Alpha if deleted	Code	Mean if deleted	Standard deviation if deleted	Alpha if deleted	Code	Mean if deleted	Standard deviation if deleted	Alpha if deleted
x_1	58.98	9.43	0.810	x_{11}	54.86	10.24	0.837	x_{21}	56.83	10.61	0.888
x_2	60.06	9.32	0.807	x_{12}	56.22	10.15	0.838	x_{22}	56.85	10.39	0.883
x_3	59.48	9.05	0.794	x_{13}	56.00	9.81	0.819	x_{23}	56.99	10.52	0.881
x_4	60.13	8.81	0.789	x_{14}	55.29	10.08	0.830	x_{24}	56.70	10.42	0.879
x_5	60.35	8.75	0.782	x_{15}	55.71	9.99	0.821	x_{25}	58.22	10.64	0.883
x_6	60.02	8.87	0.775	x_{16}	54.69	9.95	0.824	x_{26}	58.11	10.36	0.875
x_7	59.87	8.78	0.787	x_{17}	55.35	9.73	0.808	x_{27}	57.46	10.24	0.878
x_8	59.78	8.67	0.771	x_{18}	55.69	10.12	0.827	x_{28}	57.36	10.62	0.887
x_9	60.44	8.72	0.775	x_{19}	56.05	10.05	0.826	x_{29}	57.54	10.69	0.889
x_{10}	60.09	8.51	0.769	x_{20}	56.23	10.06	0.836	x_{30}	58.21	10.67	0.896

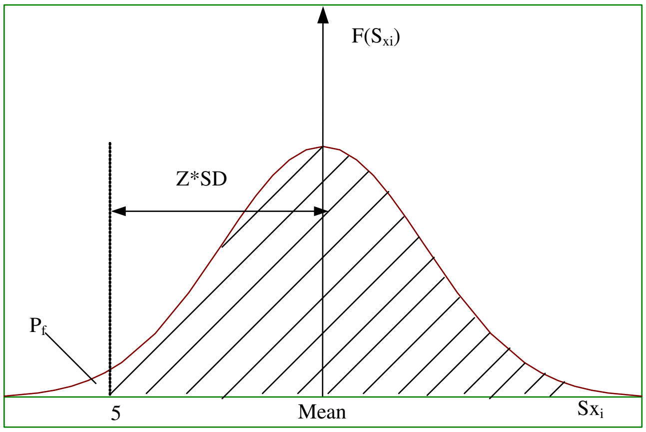

Fig. 1. Normal distribution of indicator's significance score

where P_f = possibility that the variable does not belong to the group, as shown in Fig. 1.

Therefore, calculations for the degree of membership, $\mu_{\tilde{A}}(x_i)$, can be derived with Eq. (3). The results can be found in Table 6. To identify whether an indicator is a KAI, a benchmark value should be preset. In other words, $\mu_{\tilde{A}}(x_i)$ should meet a given value (i.e., λ) if the indicator x_i is considered a key assessment indicator.

Because the survey data came from three groups of experts; namely, government officials, professionals, and project clients, different KAI fuzzy sets were determined, represented by $\tilde{A}_G$, $\tilde{A}_P$, and $\tilde{A}_C$, respectively. According to Eqs. (2) and (3) and data in Table 4, calculations for the values of the parameter Z and the degree of membership, $\mu_{\tilde{A}}(x_i)$, can be derived. The results, $\mu_{\tilde{A}_G}(x_i)$, $\mu_{\tilde{A}_P}(x_i)$, and $\mu_{\tilde{A}_C}(x_i)$, are shown in Table 6.

According to the definition of the union operator on fuzzy theory by Yager (1980), the fuzzy set can be described as follows:

$$\tilde{A} = \tilde{A}_G \cup \tilde{A}_P \cup \tilde{A}_C = \{x, \mu_{\tilde{A}_G \cup \tilde{A}_P \cup \tilde{A}_C}(x) | x \in X\} \quad (4)$$

where

$$\mu_{\tilde{A}_G \cup \tilde{A}_P \cup \tilde{A}_C}(x) = \min\left\{1, [\mu_{\tilde{A}_G}(x)^p + \mu_{\tilde{A}_P}(x)^p + \mu_{\tilde{A}_C}(x)^p]^{1/p}\right\}, \ p \geq 1 \quad (5)$$

p (i.e., the number of indicators) must be equal to or greater than 1. Obviously, the union operator will converge to the sum-operator when $p = 1$ and the union operator to the max-operator when $p \to \infty$. In this study, the number of indicators, $p = 30$, can be considered very large. Therefore, the integrated result, $\mu_{\tilde{A}}(x_i)$, was

Table 6. Degree of Membership of Indicators for KAIs

Indicator set X	Government officials		Professionals		Clients		Integrated result
	Z_G	$\mu_{\tilde{A}_G}(x_i)$	Z_P	$\mu_{\tilde{A}_P}(x_i)$	Z_C	$\mu_{\tilde{A}_C}(x_i)$	$\mu_{\tilde{A}}(x_i)$
x_0	1.394	0.918	1.636	0.949	1.476	0.930	0.970[a]
x_1	1.818	0.965	2.081	0.981	3.505	1.000	1.000[a]
x_2	1.408	0.920	0.849	0.802	1.398	0.919	0.941[a]
x_3	1.460	0.928	1.638	0.949	0.923	0.822	0.963[a]
x_4	0.889	0.813	0.660	0.745	0.976	0.835	0.846
x_5	0.909	0.818	0.478	0.684	0.883	0.811	0.834
x_6	1.345	0.911	0.858	0.805	1.493	0.932	0.945[a]
x_7	0.950	0.829	0.700	0.758	1.955	0.975	0.975[a]
x_8	0.909	0.818	0.915	0.820	2.259	0.988	0.988[a]
x_9	0.649	0.742	0.518	0.698	1.188	0.883	0.883[a]
x_{10}	0.595	0.724	0.687	0.754	1.605	0.946	0.946[a]
x_{11}	1.129	0.871	1.531	0.937	0.636	0.738	0.940[a]
x_{12}	0.211	0.584	0.505	0.693	0.000	0.500	0.693
x_{13}	0.493	0.689	0.594	0.724	0.049	0.519	0.729
x_{14}	1.235	0.892	1.004	0.842	0.347	0.636	0.896[a]
x_{15}	1.093	0.863	0.456	0.676	0.587	0.721	0.863[a]
x_{16}	1.682	0.954	1.036	0.850	0.955	0.830	0.955[a]
x_{17}	1.032	0.849	0.867	0.807	0.515	0.697	0.855[a]
x_{18}	0.971	0.834	0.541	0.706	0.694	0.756	0.836
x_{19}	0.665	0.747	0.473	0.682	0.062	0.525	0.749
x_{20}	0.286	0.613	0.342	0.634	0.218	0.586	0.642
x_{21}	1.497	0.933	1.190	0.883	0.954	0.830	0.939[a]
x_{22}	1.653	0.951	1.036	0.850	0.714	0.762	0.952[a]
x_{23}	1.403	0.920	1.083	0.861	1.117	0.868	0.928[a]
x_{24}	1.738	0.959	1.254	0.895	0.971	0.834	0.963[a]
x_{25}	0.738	0.770	0.306	0.620	0.267	0.605	0.770
x_{26}	0.724	0.765	0.323	0.627	0.374	0.646	0.766
x_{27}	1.192	0.883	0.773	0.780	0.155	0.562	0.884[a]
x_{28}	1.211	0.887	0.683	0.753	1.122	0.869	0.900[a]
x_{29}	1.161	0.877	0.770	0.779	0.539	0.705	0.878[a]
x_{30}	0.470	0.681	0.676	0.750	-0.222	0.412	0.752

[a]The degree of membership is more than 0.85.

obtained from the union $\mu_{\tilde{A}_G}(x_i)$, $\mu_{\tilde{A}_P}(x_i)$, and $\mu_{\tilde{A}_C}(x_i)$ by using Eq. (5). The results of $\mu_{\tilde{A}}(x_i)$ are shown in the last column of Table 6.

To identify the KAIs for infrastructure project sustainability from Table 6, the λ-cut set approach was adopted. The λ-cut set method can transfer a fuzzy set to a classical set. The optimal outcome is $\lambda = 1$, and the worst outcome is $\lambda = 0$. When $\lambda = 0.5$, the outcome is neither optimistic nor pessimistic. The previous study by Tervonen et al. (2009) suggests that a value for λ between 0.65 and 0.85 is effective for analysis. In this study, $\lambda = 0.85$, the upper threshold, was adopted as the criterion to select KAIs from Table 6.

The procedures for identifying KAIs can be demonstrated in a flow chart, as shown in Fig. 2. The indicator x_i was selected as a KAI if $\mu_{\tilde{A}}(x_i)$ was equal to or greater than 0.85. The set of KAIs selected is shown in Fig. 3, ranked by their degree of membership.

Discussion and Recommendation

This section discusses the findings shown in Fig. 3 and Table 6. The application of the KAIs for assessing the sustainability of infrastructure projects will be investigated subsequently.

Discussion

The state of sustainable development policy will always be above any other indicators in the KAI set for considering whether an infrastructure project should be implemented. The state sustainable development policy should be considered first before selecting KAIs for assessing the sustainability of an infrastructure project. If a project does not comply with the policy, it should be rejected. For example, China has been transferring its economy system from a planned-oriented economy to a market-oriented economy; the central government has the power to decide whether an infrastructure project is to be developed. Large infrastructure projects at the national level will be carefully examined and some vetoed by central government. Major infrastructure projects at the local level, such as an underground railway, have to be approved by the central government.

According to the identification of the KAIs shown in Fig. 3, eight economic-dimension of KAIs exist. The indicator "the analysis on the market supply and demand" is ranked as the most important indicator because the implementation of infrastructure projects should account for the demand by the market. Without considering the market, the consequence of the project implementation may be failure. For example, in some previous research, some infrastructures have been shown to be unused or used inefficiently because of an insufficient number of users (Harry 2006). Other economic-dimension KAIs include "financial risk," "life cycle benefit," "project budget," "internal return ratio (IRR)," "life cycle cost," and "payback period."

Five KAIs make up the social dimension. The indicator "public safety" is ranked the most important in this group. It is often reported in China that the number of casualties in construction safety accidents has reached three per day (Fang et al. 2001). One of the primary reasons for this is poor safety management. Other KAIs in the social dimension include "effect of local development," "scale

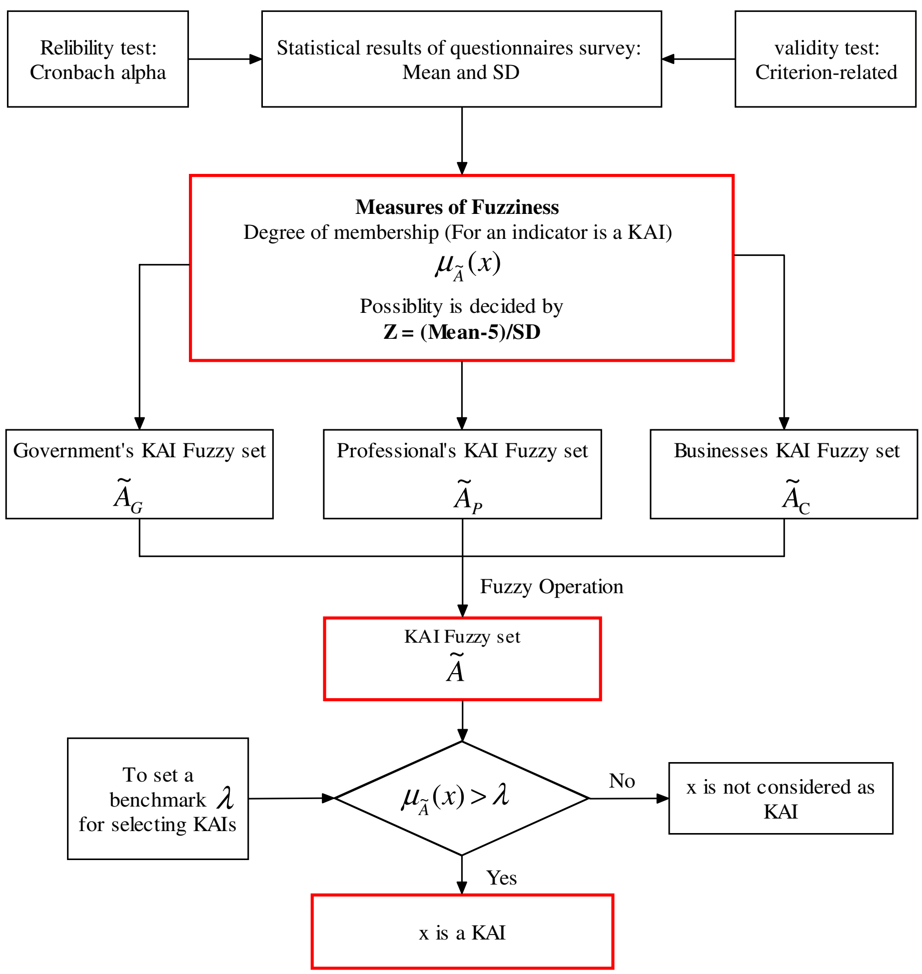

Fig. 2. Procedure for identifying KAIs from fuzzy set theory

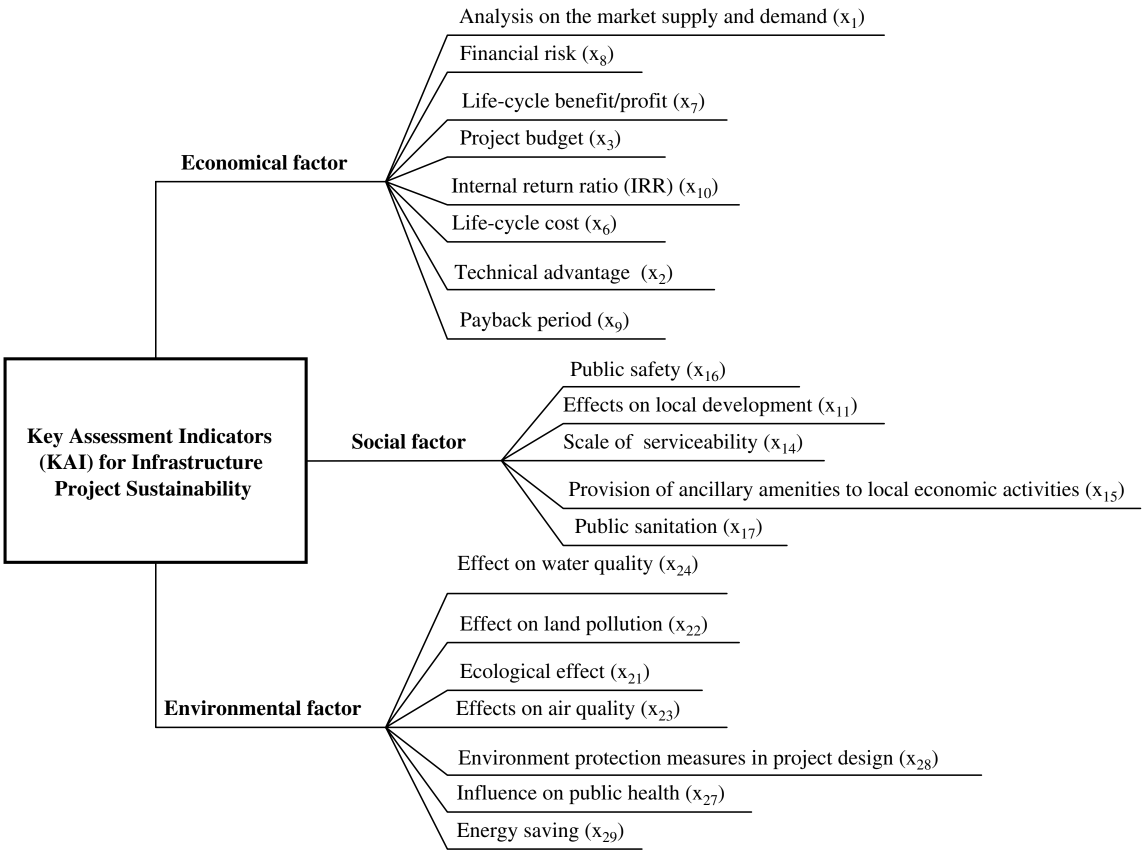

Fig. 3. KAIs for infrastructure project sustainability

of service ability," "provision of ancillary amenities to local economic activities and public sanitation." These indicators have a significant influence on community services across many aspects when operating an infrastructure project.

Seven KAIs have been identified in the environmental dimension. The indicator "effect on water quality" is ranked the most important. Water pollution has aroused increasing concerns in China. According to a recent investigation, 33% of rivers are polluted badly. In Zhejiang Province in 2006, the water quality grade was below Grade V, which is the lowest grade in China [Water Resources Office of Zhejiang Province (WPOZJ) 2008]. Many water pollution problems are attributable to the improper implementation of infrastructure projects. Water pollution has become an unsustainable problem; thus, it is most important to consider this factor when implementing a construction project. Other KAIs in the environmental dimension include "effect on land pollution," "ecological effect," "effects on air quality," "environment protection measures in project design," "influence on public health," and "energy saving." In China, the requirement for an environmental impact assessment (EIA) for infrastructure projects has been enforced by the government since 2003 as *The Law of the People's Republic of China on the Environmental Impact Assessment* (State Council of the People's Republic of China 2003).

The sustainability of infrastructure projects is affected by many factors; key factors exist that have more influence on sustainability. In this context, the identification of the KAIs in this study highlight the major areas in which more effort should be made to adopt effective methods to improve infrastructure project sustainability.

Case Study: KAI Application

The sustainability of a project should be in accordance with the state's macroeconomic and sustainable development policies. In fact, the development of a large infrastructure project must be approved by both the local and the central government. China is a country with limited per capita resources; thus, the state's macro policy must emphasize the implementation of sustainable development. Therefore, to identify whether an infrastructure projects can contribute to sustainable development or not, the first thing is to ensure that the project complies with the national macroeconomic policy. If the project meets the premise of the macro policy, further evaluation on the economic, social, and environmental factors can be conducted.

The case study chosen for this study was the metro project in Hangzhou, which was approved by the National Development and Reform Commission. This project is a large infrastructure project, including eight lines over 278 km. The budget for the project is RMB$100 billion. The project commenced in 2006, and it is planned for completion in 2050. The first phase of the project was budgeted for RMB$22 billion and will be complete in 2011. The project was chosen for a case study because this research team has good contacts with the project management team, and relevant project data can be obtained effectively for analysis.

To demonstrate the application of the model introduced in this study, four scenarios were designated for this case study. The four scenarios represent four optional development strategies for this metro project.

- Scenario 1: Building a city loop—This development strategy can bring maximum social benefits but will encounter financial difficulty to complete the project.
- Scenario 2: Connecting the old with the new city area and bypassing special protected areas (e.g., public parks)—With this development option, maximum economic benefits can be gained from developing the new metro infrastructure because land prices will be increased in the areas around the new metro

infrastructure. Sufficient finances can be secured by the selling of land.

- Scenario 3: Connecting the old with the new city area and passing through special protected areas—This strategy will also bring economic benefits from developing the new metro infrastructure. The land price can be increased in the areas around the new metro infrastructure, and sufficient finances can be secured by the selling of land. However, the ecological and environmental performance of special protected areas will be affected by the development of the new infrastructure. This is not in line with the government's sustainable development principle and will be rejected. Thus, this option will not be included in the subsequent discussion.
- Scenario 4: Building a light rail—This development strategy requires less investment and construction cost, and it can yield early returns. However, this development option will generate significant noise pollution, particularly during its long-term operation stage.

For the discussion about the case study, five professionals involved in this project were invited to provide their judgments on the performance of each KAI listed in Fig. 3 for each development scenario considered. A five-point Likert scales method was employed to grade the indicators, 5 meaning excellent, 4 good, 3 moderate, 2 pass, and 1 poor. The total score of each factor was adopted as the evaluation score. The average scores for all KAIs from the responses from the five professionals are shown in Table 7.

In the table, 20 KAIs were adopted, including eight economic KAIs, five social KAIs, and seven environmental KAIs.

To get the group score for the three dimensions, namely, economic, social, and environmental, a standardization can be adopted. For example, the total score of the eight economic KAIs for Scenario 1 was 25, and this score can be standardized by multiplying the score by the coefficient 20/8, making the standardized score for the economic dimension of Scenario 1 62.5. Similarly, the standardized score for Scenario 1 for the social dimension was 92 (i.e., 23 multiplied by 20/5) and for the environmental dimension 77.1 (i.e., 27 multiplied by 20/7).

The calculated standardized scores for each group of KAIs in the other scenarios are shown in Table 7. The criteria for judging the benchmark sustainability of this infrastructure can vary among different projects. Nevertheless, a score of 70 can represent a reasonable level of sustainability standard; thus, 70 was used in this study as an effective demarcation for choosing the final option. This demarcation was presented to the five professionals and supportive responses were received. As a result, according to Table 7, because the economical dimension received a standardized score of 62.5 in Scenario 1, which was less than the benchmark score 70, it was not considered further.

Having rejected the Scenarios 1 and 3, only Scenarios 2 and 4 remained for comparison. To select an effective option between the two scenarios, a weighted score among the economic, social and environmental dimensions was required. The weights among the three dimensions can vary when different types of projects are considered. In this case study, the five professionals were invited to join the discussion by giving weighting values. From this discussion, an agreed-upon distribution was determined: the economic dimension

Table 7. Multioptions Evaluated on KAI

Group	Indicator	Code	Scenario 1	Scenario 2	Scenario 4
			Score	Score	Score
Economical aspect (0.35)	Market supply and demand analysis	x_1	5	5	4
	Financial risk	x_8	2	4	4
	Life-cycle benefit/profit	x_7	3	4	4
	Project budget	x_3	2	4	5
	Internal return ratio (IRR)	x_{10}	3	3	5
	Life-cycle cost	x_6	4	4	4
	Technical advantage	x_2	4	4	3
	Payback time	x_9	2	3	5
	Total score		25	31	34
	Total score after standardization = Total score × 20/8		62.5	77.5	85.0
Social aspect (0.36)	Public safety	x_{16}	5	4	3
	Effects of local development	x_{11}	4	5	5
	Scale of infrastructure serviceability	x_{14}	5	4	4
	Ancillary amenities to local economic activities	x_{15}	4	4	4
	Public sanitation	x_{17}	5	4	4
	Total score		23	21	20
	Total score after standardization = Total score × 20/5		92.0	84.0	80.0
Environmental aspect (0.29)	Water quality effect	x_{24}	4	4	4
	Land pollution effect	x_{22}	4	4	3
	Project ecological effect	x_{21}	5	4	3
	Effects on air quality	x_{23}	4	4	3
	Environment protection measures in project design	x_{28}	3	4	3
	Project influence on public health	x_{27}	4	4	4
	Energy saving	x_{29}	3	4	5
	Total score		27	28	25
	Total score after standardization = Total score × 20/7		77.1	80.0	71.4

would be 0.35, the social dimension would be 0.36, and the environmental dimension would be 0.29, as shown in Table 7. Nevertheless, the limitation of using a limited number of responses was appreciated, but it was considered effective for the demonstration of a case study. Consequently, the weighted scores for the two scenarios were calculated as follows.

The weighted score for Scenario 2 is

$$(0.35 \times 77.5) + (0.36 \times 84.0) + (0.29 \times 80.0) = 80.6$$

The weighted score for Scenario 4 is

$$(0.35 \times 85.0) + (0.36 \times 80.0) + (0.29 \times 71.4) = 79.3$$

Accordingly, Scenario 2 was selected in this case study. In other words, the development should connect the old city with the new city and bypass the special protected areas of the city.

Conclusion

Infrastructure projects play major roles in economic, social, and environmental activities, particularly in developing countries. Their sustainability performance should be properly assessed when considering implementation. Because effective assessment indicators are unavailable in practice, the sustainability of infrastructure projects usually are not assessed effectively. This paper, therefore, introduced a set of key assessment indicators (KAIs) for assessing the sustainability of infrastructure projects. Fuzzy set theory was adopted for developing the KAIs, which increases the adequacy of the indicators' application. Typical KAIs identified included the analysis of the market supply and demand, financial risk, public safety, effects on local development, effects on water quality, and effect on land pollution. The detailed list of KAIs is provided in Fig. 3. By using KAIs, the sustainability performance of an infrastructure project can be assessed bycalculating a weighted sustainability score. The application of KAIs can help decision makers identify an optimal solution among alternatives, which presents maximum sustainability performance score. A practical case, namely, an urban metro infrastructure project, was used to demonstrate an application of KAIs. In this case, four alternative development plans were considered. Scenario 2 was considered the best solution. This study provided an alternative methodology to assess the sustainability performance of infrastructure projects. However, the limitations of the study are appreciated, particularly, (1) the application of KAIs is demonstrated only through a case study; (2) other important factors such as emissions have not been included. These limitations may be attributable to the largely the limited scope of this study in the Chinese context. Nevertheless, the findings from this research can be valuable references for studying similar topics in other countries.

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