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Key Sustainability Indicators for Infrastructure Systems: An Australian Perspective

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Abstract
Development of infrastructure projects generally receives vast amount of capital investment in any country. However, yet one of the main challenges in the provision of physical infrastructure is meeting the growing demand for new infrastructure, while maintaining, upgrading or replacing aging infrastructure. This has led to the recognition of the importance of ensuring infrastructure sustainability during its life cycle. Therefore, in an attempt to investigate current Australian infrastructure sustainability practices, a pilot questionnaire survey was conducted for gathering data required to identify key sustainability indicators (SI's) and to draw upon practitioners' opinions regarding the importance of SI's in assessing sustainability performance of typical infrastructure projects. The research reported upon forms part of a larger study that aims to develop an integrated expert decision support system for sustainability performance assessment. This involves identification of relevant SI's and investigation of practitioners' preferences of their use.

Keywords
Sustainability Indicators, Infrastructure Systems, Australia

1. Introduction

Sustainable development (SD) is a concept with multi-dimensional aspects. Through a pattern of resource use, SD aims to enhance both economic and social growth, while minimizing negative environmental impacts. Vital contributors to SD are the infrastructure systems which have a huge impact on the spatial and temporal dimensions. Examining the performance sustainability of that type of systems requires an interdisciplinary approach involving social, environmental, economic, and engineering sciences. This hard and complex process necessitates a proper assessment of the diverse conditions under which infrastructure systems operate. Thus, among sustainability assessment methods, the indicator approach is the most promising in terms of transparency, consistency over time and usefulness in the decision-making process (OECD, 2002). Indicators have been considered as a primary method to transfer sustainability theory into practical measurement tools to measure sustainability (Bockermann et al., 2000). In the infrastructure context, many studies have utilized SI's to produce sustainability assessment frameworks aiming to quantify sustainability performance (Dasgupta & Tam, 2005; Koo & Ariaratnam, 2008). However, the major limitation with these frameworks/models, though, is their failure to take into account the interaction among SI's which may lead to unclear picture about the sustainability of the infrastructure systems. Another weakness lies in the lack of considering the uncertainty conditions in the sustainability assessment process. Further information on this issue could be found elsewhere (Alsulami & Mohamed, 2010). Therefore, a research project was instigated to overcome the above limitations and to develop an integrated expert decision support system for sustainability performance assessment. As shown in Figure 1, the research methodology begins with conducting a comprehensive literature review to nominate an initial set of SI's. Then, it utilizes a questionnaire survey to select key SI's. This is followed by conducting interviews with experts, with the aim of modeling the interaction(s) among selected SI's, employing fuzzy cognitive mapping (FCM). Finally, a real world case study will be used to illustrate the validity of the developed model.

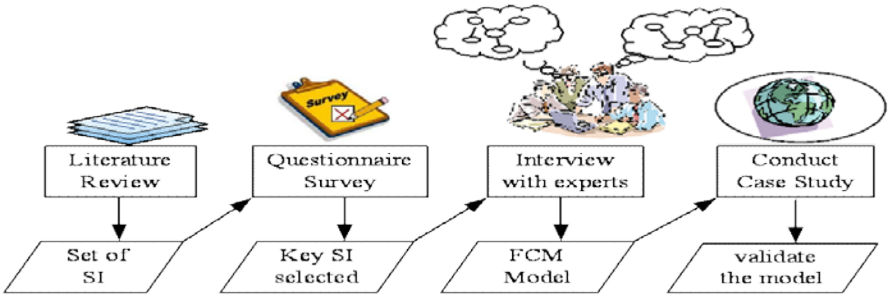

Figure 1: Research Methodology

This paper reports on the results obtained at the second stage of the research methodology where a research questionnaire instrument was utilized to determine key sustainability aspects and their indicators. The focus herein is on the relative importance and frequency of utilization as practised by the Australian construction industry. The rest of this paper is organized as follows. Next, section 2 gives overview of FCM technique. Section 3 briefly discusses related work. Section 4 outlines the research methodology adopted. Section 5 discusses and presents the results, and finally, Section 6 concludes the paper.

2. Overview of Fuzzy Cognitive Map (FCM)

FCM methodology is an extension to cognitive maps, which has been applied in economics, sociology and political science (Kosko, 1986). It is a modeling methodology for complex systems, derived from the combination of two methodologies, namely fuzzy set theory and neural networks. The FCM is a signed fuzzy graph with feedback, consisting of nodes and weighted interconnections. It describes the behavior of a system in terms of nodes; each node represents a variable or a characteristic of the system (Dickerson & Kosko, 1997). Nodes are connected by signed and weighted arcs representing the causal relationships that exist among them. A simple graphical representation of FCM is depicted in Figure 2.

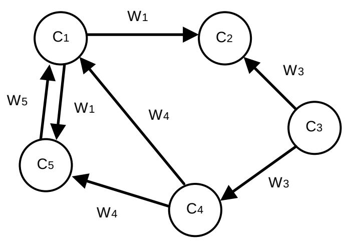

Figure 2: A typical FCM (Kosko, 1986)

Measuring the sustainability of infrastructure systems is a complex process, due to the complex nature of the infrastructure systems. Many authors have acclaimed the capability and effectiveness of FCM in modeling complex systems. The main advantage of FCM technique, it is capability in modeling the interaction among different variables. According to Niemeijer and de Groot (2008), modeling interaction among SI's is useful in numerous ways: it highlights the true complexity of the sustainability interactions; it can help identify key indicators thereby reducing the number of indicators necessary for sustainability reporting; and jointly, this can lead to more efficient indicator-based reporting and better decision-making. Thus, FCM has been selected as appropriate modeling technique.

3. Sustainability Issues

In the context of infrastructure provision, there is a lack of globally accepted SI's that can be utilized in defining project objectives at different stages of project lifecycle. To further complicate the matter, circumstances, activities and priorities for SD differ from one country to another (Anagnostopoulos et al., 2004). Thus, several recent attempts have been made in different countries, to generate set classifications of sustainability criteria, and indicators, specifically related to the performance of infrastructure projects. For example, Foxon et al. (2002) conducted a study to develop sustainability criteria as relevant to the British water industry. Ugwu et al (2006) prioritised SI's of an infrastructure project in the Hong Kong context. In South Africa, Ugwu and Haupt (2007) identified key performance indicators for infrastructure sustainability based on a local survey. More recently, Fernandez-Sanchez and Rodriguez-Lopez (2010) prioritised SI's of infrastructure projects in the Spanish context. And, Shen and Zhang (in press) introduced key SI's for assessing the sustainability performance of infrastructure projects based upon data collected from a questionnaire survey targeting experts in the Chinese construction industry. Despite all of these attempts, the current literature does not provide sufficient information about how the experts and practitioners perceive the level of importance and the degree of utilization of SI's as related to infrastructure systems, especially in the Australian context.

4. Methodology

In this research, a qualitative approach (attitudinal research) was adopted to identify the level of importance, and frequency of use of sustainability aspects and their indicators. According to Naoum (1998), attitudinal research, is used to subjectively evaluate the opinion of a person or a group of people towards a particular attribute, variable, factor or question.
The sustainability aspects and the list of SI's under consideration were derived from an extensive literature review of published materials in academic and industry reports, and government documents. Then, a questionnaire survey was used as a research instrument to collect data from selected target experts. A total of 53 experts were selected based on namely their experience in sustainability assessment for infrastructure systems. A total of sixteen responses (about 30.1%) were received in the right format. This response rate is considered adequate for a survey focusing on acquisition responses from industry practitioners (Alreck and Settle, 1995). The respondents represent infrastructure owners' organizations and consulting companies (75% are Consulting companies, 25% of Owners' organizations). The first two questions of the survey were related to sustainability aspects. The respondents were asked to rank the main sustainability aspects based on their importance, and to indicate the sustainability aspects they usually consider in their assessment for sustainability performance.

Respondents were also asked to assign a ranking order for the listed indicators within each category (i.e. aspect) according to the perceived importance. For example, under the economic indicators category, there were eight indicators, respondents were requested to assign the rank number (1) for the most important indicator, and number (8) for the least important indicator among all economic indicators a weighted average scoring method was used to analyze collected data regarding indicator frequency of utilization. For example,, respondents were asked to select a score based on a four-point likert scale from 1 to 4 (where 1 is never utilized and 4 is often utilized). Based on the frequency analysis, the aggregate response was then calculated to determine the ranking of each indicator. The average frequency of utilization level for each indicator was calculated, using the following formula (Arditi & Chotibhongs, 2005):

$$\text{Average frequency} = \frac{(4 \times A)+(3\times B)+(2 \times C)+ (1 \times D)}{(A+B+C+D)}$$

where A= number of respondents who answered often, B sometimes, C seldom, and D never.

5. Results and Discussion

5.1 Sustainability Aspects Ranks

As can be seen in Table 1, the economic aspect of sustainability is ranked the highest as most relevant aspect to the provision of sustainable infrastructure systems by the total group of surveyed experts. Moreover, it has the highest frequency of use, as reported by the majority of respondents, this result is not unexpected, as it is quite common practice, for the economic factors to be assessed in the first instance.
The environmental aspect ranked second most relevant. It has also come in the second rank in terms of frequency of utilization, as 14 out of 16 experts indicated that they are utilizing this aspect in their work. This result confirms that the environmental movement won its battle in Australia, even at infrastructure system scale. The technical and social aspects ranked third and fourth, respectively. Respondents seem to have given social issues low priority of relevance to sustainable infrastructure systems. Interestingly, only 9 out 16 experts considered the social aspect in their practice.

It can be noticed that economic, environmental, and technical aspects have nearly similar ranking in both relevance to the provision of sustainable infrastructure, and regularity of utilization by participated experts. The social aspect has not shared the same level of utilization, though, which means that this particular aspect continues to lag behind the other sustainability aspects. There are other aspects that were considered by some experts as independent sustainability aspects. These aspects are equity, ethics, and governance. However, those aspects were only considered by two experts. It could be argued that these independent aspects could be covered by one or more of the four sustainability aspects adopted in this study. For instance, equity has been covered by the affordability indicator under economic aspect. Likewise, job opportunities are covered under the social aspect.

Table 1: sustainability aspects

Sustainability Aspect	N=16			
	Relevance		Frequency	
	Aver.	Rank	Aver.	Rank
Economic	2	1	0.94	1
Environmental	2.25	2	0.88	2
Technical	2.75	3	0.81	3
Social	3.125	4	0.56	4

5.2 Sustainability Indicators Ranks

Table 2 shows SI's according to their importance based on experts' perceptions, and based on their frequent utilization in practice.

Table 2 sustainability indicators

Aspect	Indicators	N=16			
		Importance		Frequency	
		Aver.	Rank	Aver.	Rank
Economic	Capital cost	2.25	1	1.0	1
	Life cycle cost	3.69	3	0.87	4
	Cost of employment	6.75	8	0.64	8
	Financial returns	2.38	2	0.89	3
	Financial risk exposure	3.94	4	0.92	2
	Improvement of regional economy	6.06	6	0.71	7
	Affordability	4.75	5	0.86	5
	Willingness to pay	6.19	7	0.75	6
Technical	Performance	1.25	1	0.97	1
	Reliability	2.38	2	0.97	1
	Durability	3.44	3	0.91	2
	Flexibility and adaptability	4.19	4	0.86	3
	Resilience to recover	5.19	6	0.75	5
	Vulnerability to failure	4.56	5	0.84	4
Environmental	Air pollution	3.38	2	0.83	3
	Water pollution	3	1	0.89	1
	Noise pollution	3.56	3	0.83	3
	Waste generation	4.88	5	0.83	3
	Visual impact	6.25	8	0.75	5
	Ecological impacts	4	4	0.87	2
	Natural resource utilization	5.5	7	0.79	4
	Climate change emissions	5	6	0.75	5
Social	Direct employment	4.06	4	0.73	5
	Impact on safety	1.94	1	0.98	1
	Risks to human health	2.44	2	0.94	2
	Stakeholder participation	3.88	3	0.84	3
	Public awareness & understanding	4.88	5	0.84	3
	Heritage and culture	5.06	6	0.79	4
	Indirect employment	5.81	7	0.66	6

5.2.1 Economic Indicators

As can be noticed in Table 2, the most important and frequently utilized indicator of the economical aspect is *capital cost*, as it was ranked first by all experts. This is because in case of public infrastructure projects, the *capital cost* is usually the main driver indicator in economic analysis over other economic indicators. In other words, when cost-benefit analysis being conducted, other economic indicators would have lesser role compared with the capital cost. So, practitioners are first concerned with *capital coast* value when assessing economic sustainability. The *cost of employment* was ranked as the least important and least frequently utilized indicator. This result indicates that the *cost of employment* indicator has negligible role in the sustainability assessment from both owners and consultants' points of view. This indicator, however, might have taken a different ranking if construction contractors were part of this survey, as they are typically concerned with cost of employment.

Notably, *improvement of regional economy* indicator was ranked the second lowest frequently utilized indicator, and sixth in terms of its importance. This result was unexpected due to well-recognized role of infrastructure projects in the enhancement of regional economy. A possible explanation of this result is that, participants could have been more interested in the micro (system level) than macro objectives of the sustainable infrastructure systems.

From the above, it can be concluded that the, *capital cost*, *affordability*, and *cost of employment* indicators have importance ranking that are similar to that of their level of utilization. For remaining indicators, the difference between their importance rank and utilization rank was marginal (in many cases it was no more than 1 unit), for example, *financial returns* ranked second on its importance, and ranked third on its utilization level.

5.2.2 Technical Indicators

In the technical aspect, six indicators were listed in the survey. They included quantitative indictors such as reliability and durability, and qualitative indicators such as system performance. As can be seen in Table 2, the *performance* indicator, followed by the *reliability* and *durability* indicators are the top three indicators in this aspect. Such high ranks confirm a recent study (Chong et al., 2009), where system's performance and reliability were considered as important issues that must be included in sustainability performance frameworks.

The *vulnerability to failure* and *resilience to recover* were ranked as the least important and frequently utilized indicators. This is despite, the role of the resilience concept and its function toward reaching sustainable infrastructure systems has been generally discussed in recent years (Friesz et al., 2010; Wang & Blackmore, 2009). It appears that there is still contention with respect to objectively measuring resilience in the scientific community. Moreover, there is no well established method that can be used for measuring resilience of an infrastructure system (Boyle et al., 2010). Thus, such shortcomings that relate to both indicators have been reflected in the study findings.

It is worth noting that flexibility and adaptability of the system, for future change, was considered by the literature as one of the most important indicators. It is not surprising, therefore, that this indicator has high level of utilization in practice, as it was ranked third. Finally**,** it is worth reporting that ranking orders for both level of importance and level of utilization were similar for each of the six indicators.

5.2.3 Environmental Indicators

The environmental indicators were selected to represent the environmental impact stemming from the project at any stage of the infrastructure lifecycle. Eight indicators under this aspect were used in the survey. As can be seen in Table 2, the most important and frequently utilized indicator is *water pollution*, as it was ranked first by all respondents. *Air pollution* was ranked second. This is expected as *air pollution* consistently rates as a major concern for Australian urban communities (DEH, 2004).While the second most frequently utilized indicator, as perceived by the participants, is *ecological impacts*. Naturally, the priority of those two indicators depends on the project lifecycle stages. As it has been found in most sustainability assessment reports, the assessing team typically looks at the degree of *ecological impacts* that might occur as a result of development of proposed projects. In contrast, *air pollution* is usually considered after the event (i.e. during the operational stage of the system).

It is worth reporting that the two groups of survey participants had different views as to the level of importance of each indicator (detailed results are not presented in this paper due to space limitation). For instance, the *climate change emissions* indicator was ranked third by owners, while it was ranked seventh by consultants. This is perhaps due to climate change being on top of current affairs nowadays, and concerns about climate change have been strongly advocated by the Australian Federal and State Governments. For example, a new legislation (Integrated Transport Act 2010) that enacted by Victorian Parliament which is recently released in 2010, has outlined a new framework for assessing transport schemes emphasizing sustainability. In this assessment framework, it has required that the *GHG* indicator to be quantified for any new transport system scheme. This is may be justified why the owners have considered the *climate change emissions* indicator at the top.

The difference between importance and utilization level ranks is noticeable among environmental indicators particularly in the lower rank indicators. For example, the *natural resource* indicator was ranked seventh in terms of its importance whereas it was ranked fourth in terms of its utilization level in practice. As for the top three indicators, there is no significant difference regarding their rankings. *Water pollution* was ranked first for both importance and utilization level. *Noise pollution* was ranked third for both variables as well. *Air pollution* was ranked second for its importance, and third for its utilization level.

5.2.4 Social Indicators

One area that needs more research effort in the field of sustainable infrastructure systems is social aspect. As this is hugely being neglected by the research community, and only just recently has drawn some attention towards its important role in achieving sustainability objectives in the context of infrastructure development (Edum-Fotwe & Price, 2009). Since most of Social indicators are qualitative indicators (Ashley et al., 2008), they have been considered as most difficult to deal with among all sustainability indicators in terms of their quantification.. Thus, it is interesting to figure out their utilization level in practice. In this study, seven social indicators were considered.

As can be seen in Table 2, the *impact on safety* indicator was ranked first by participants. The *risk to human health* indicator was ranked second. This finding further reinforces early research results (Ugwu et al., 2006), where safety and health indicators were ranked on the top of whole sustainability indicators. Surprisingly, the *stakeholder participation* was ranked third most important indicator. As there is no universal agreement within the scientific community on *stakeholders participation* and inclusion definitions, this indicator is considered one of the most difficult indicators to quantify reliably. As it is usually considered difficult without spending more efforts on public encouragements, funding and education (Hurley et al., 2008). However, it is interesting to note that there is a growing concern from industry practitioners about the important role of *stakeholder participation*, and *public awareness and understanding* towards achieving sustainable development. The *heritage and culture* indicator was ranked the second lowest significant indicator. This rank would perhaps be much higher if this survey were conducted in a country that has more heritage buildings with potential negative impact from new infrastructure development. Again, this finding confirms the locality of developed indicators – any region or country would have its own sustainability priorities.

In terms of degree of difference, there is no difference between importance and utilization ranks for the top three social indicators. Nevertheless, the difference has been noticed in the remaining indicators. For instance, the *public awareness and understanding* indicator was ranked fifth in terms of its importance for attaining sustainability in infrastructure system, while it was ranked third in terms of its utilization level.

6. Conclusion

Infrastructure systems have major roles toward achieving sustainable development objectives. Thus, an accurate quantification of sustainability performance of those systems should be reached via appropriate utilization of the 'right' sustainability indicators. This paper presents the results of a questionnaire survey that was undertaken to explore the perceptions of a sample of Australian owners and consultants regarding the importance of sustainability aspects and SI's that should be used to evaluate sustainability performance for infrastructure systems. The current level of utilization of those aspects and their indicators has been determined. As this set of indicators has been identified, this research study aims to develop a fuzzy cognitive map that underpins the development of a decision support system that could be used for assessing sustainability performance for typical infrastructure systems.

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