

INCORPORATING SYSTEM COMPLEXITY IN SUSTAINABILITY ASSESSMENT FOR CIVIL INFRASTRUCTURE SYSTEMS: AN INNOVATIVE APPROACH

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ABSTRACT

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 civil infrastructure systems (CIS) which have a huge impact on the spatial and temporal dimensions. Examining the performance sustainability of CIS 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 the CIS operates. Nevertheless, to date, many attempts have been made to develop sustainability performance assessment frameworks for CIS. All of these frameworks have failed to consider two key facts underpinning the SD concept, namely the interaction between sustainability aspects; and the temporal inter-relation between different life cycle phases for CIS. This paper introduces a novel approach utilizing fuzzy cognitive mapping to model the interaction among sustainability indicators in the context of CIS. The proposed approach considers system complexity through modelling dynamic interaction among sustainability indicators, and the dynamics interaction between the CIS itself and its neighbourhood. Also, it considers the temporal inter-relationship between the different life cycle phases for the CIS, by adopting life cycle-based sustainability indicators.

Keywords: Civil Infrastructure Systems, Complexity, Fuzzy Cognitive Maps, Sustainability.

INTRODUCTION

There are many definitions for the sustainable development concept, which means there is no universally accepted definition. However, the most frequently used definition is that produced by the World Commission on Environment and Development (WCED), included in the Brundtland Report in (1987); sustainable development was defined as “meeting the needs of the present population without compromising the ability of future generations to meet their own needs.” Many authors such as Gow (1992) and Qizilbash (2001) argue that the Brundtland’s definition is simple but rather vague. Thus, a particular definition of sustainable development for different industries is required. In the context of civil engineering, the American Society of Civil Engineers (2004) has proposed the following definition: “Sustainable Development is the challenge of meeting human needs for natural resources, industrial products, energy, food, transportation, shelter, and effective waste management while conserving and protecting environmental quality and the natural resource base essential for future development”.

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). In the infrastructure context, many studies have utilized sustainability indicators to produce sustainability assessment frameworks aiming to quantify sustainability performance. Dasgupta and Tam (2005), for example, developed a framework using the multi-layered framework of civil infrastructure system (CIS) indicators. Ugwu et al. (2006) developed another model known as sustainability appraisal in infrastructure projects to perform sustainability assessment at the project level. Koo and Ariaratnam (2008) developed a model for specifically assessing the sustainability of underground infrastructure. However, the major limitation with these frameworks/models, though, is their failure to take into account the complexity among sustainability aspects which may lead to unclear picture about the sustainability of the CIS. Another weakness lies in the lack of considering the uncertainty conditions in the sustainability assessment process.

This paper introduces an innovative approach to modelling the interaction among sustainability indicators in the context of CIS. The sustainability indicators have been classified into two groups. The first group represents sustainability of the CIS whereas the second group represents sustainability of the region (urban neighbourhood) that will be affected by the CIS. Hence, the proposed approach will model interaction among sustainability indicators at both levels. In developing a sustainability indicators dynamic model, this paper utilizes fuzzy cognitive maps (FCM), which is a soft computing technique that is used to model and describe the behaviour of dynamical systems. The next sections present the research rationale and adopted methodology.

SUSTAINABILITY AND CIVIL INFRASTRUCTURE SYSTEMS

Sustainable infrastructure can be defined as, “physical assets that provide net benefits to a community, its neighbours, and the environment on a long-term basis” (Brown, 2002). Thus, a primary objective of sustainable infrastructure is to improve the harmony between the built and natural environments by mitigating negative environmental and enhancing social as well as economic consequences related to infrastructure performance. Thus, it is not difficult to appreciate the relationships between infrastructure and SD objectives.

Indeed, there is a clear relationship between infrastructure and all three aspects of SD. In terms of the economic aspect, many authors have emphasised the relationship between infrastructure and economic growth. Ingram and Fay (2008), for example, pointed out that infrastructure is a key determinant of economic growth, and that sustainable economic growth requires accelerated infrastructure investment. Further, Parkin and Sharma (1999) reported that for every one percentage point increase in the infrastructure stock, there was an associated one percent increase in gross domestic product. The economic aspect represents part of story as the social aspect is also involved. Certainly, Mirza (2006) stated that well-functioning infrastructure in a country is essential for its sustained economic growth, international competitiveness, public health and overall quality of life. In the same way, infrastructure development plays a significant role in determining environmental sustainability since it locks into consumption patterns of natural resources as well as pollutions issues.

Most of previous studies have referred to the macro level of sustainability of CIS (i.e. the interaction between the CIS and the economic, environmental and social systems). Thus, to ensure reaching the true meaning of sustainability, we should look through a holistic perspective which includes both macro and micro levels. Such an approach will enable an understanding of the true meaning of sustainability within the context of both levels. The next section reviews sustainability of CIS at the micro level.

In the literature, there is disagreement on the definition of system sustainability at the micro level, which made it until now a questionable concept (Hessami et al., 2009). As sustainability is related to the future, so system sustainability can be viewed from the perspective of longevity and survivability. In general, for instance, Hansen and Jones (1996) defined system sustainability as “the probability that a particular system will not meet specified criteria for failure during a particular future period”. In a more comprehensive manner, Zimmerman and Sparrow (1997) defined infrastructure sustainability as: the ability to maintain infrastructure systems at some desired level of performance or to change their performance at some desired rate and direction.

Therefore, the sustainability of an infrastructure system depends on its ability to perform and to provide the service for which it is created. From a system point of view, an infrastructure system might be affected by external factors that make changes in its performance, for instance, a natural or man-made disaster (Freeman & Warner, 2001; Stewart et al., 2006). Internal factors might also affect CIS performance, such as the management, operational and maintenance systems (Yang et al., 2007). However, to achieve sustainability objectives one should start by defining the meaning of sustainability of CIS at both macro and micro levels. Consequently, sustainability of CIS performance assessment should take into account that unified definition as starting point to assess CIS performance in a more comprehensive way.

LIMITATION OF SUSTAINABILITY ASSESSMENT MODELS

Despite the fact that several studies have been conducted into SD in general, and in the construction industry in particular, still much research work should be conducted towards promoting sustainability principles. A recent study by Yuan and Yang (2008) stated that, “the construction sector is at infant stage and much more has to be done to make all construction work more sustainable.” Furthermore, the authors added that, researchers often ignore specific sectors in construction, for instance infrastructure. Another recent study supports this viewpoint; Koo and Ariaratnam (2008) emphasised the overall research of infrastructure sustainability is still in its infancy stage. This is a key factor that motivated conducting the research reported herein.

Sustainability Measurement does not Consider Systems Complexity

Indicators have been considered as a primary method to transfer sustainability issues into quantitative or qualitative measures of economic, environmental and social performance (Azapagic & Perdan, 2005). Thus, indicators that are considered related will lead to constructing a picture of systems (Bossel, 1999). Therefore, in conducting performance assessment, it is essential to take into account those indicators relevant to the system under review. Also, as system components connected to each other, in the same way the indicators should take into account their interaction to avoid any misleading might occur resulting from ignoring the interaction. Although, some

researchers have explained relationship among three aspects of sustainability. Dyllick and Hockerts (2002), for example propose efficiency and effectiveness concepts in order to understanding the interaction among sustainability aspects. However, so far, one of the most general inadequacies of sustainability indicators is still the failure to link them together, which might lead to indicators failing to represent accurate information (Murray et al., 2009; Wilson et al., 2007). Recently, many studies have recommended producing developed performance measurements that show an understanding of the relationships between indicators and their impact on the final decision. Matar et al. (2008) stated, “much of the future study by researchers from both fields of construction and environmental sciences should focus on identifying the relative weights of sustainability parameters and the dynamics between parameters.” Moreover, Jeon (2007), has argued that future research must incorporate the broader environmental, economic and social impacts of transportation systems by modelling the interactions among these sustainability dimensions. In addition, In addition, Nishijima (2009) postulated that there is needed to develop more sophisticated models that incorporate the interactions among the sustainability components that including the socio-economic roles of infrastructure as well as environmental aspects such as exploitation non-renewable resources and protection of the biodiversity. Also, few studies have recommended the need for further explanation of the complexity of infrastructure with other systems in the sustainability context. For instance, Little (2005) believe that the infrastructure system is complex and its performance is influenced by interaction with the greater urban region and other infrastructures. Therefore, exploration study of these relationships might lead to considerable enhancements in infrastructure sustainability. This fact has led to the recognition the importance of capturing interactions among sustainability indicators, as well as clarifying the relationships among sustainability indicators.

Uncertainty Problem in Sustainability Assessment

Uncertainty arises due to lack of knowledge, which is caused by several factors such as limited and inaccurate data, measurement error, limited understanding, imperfect models, subjective judgments, ambiguities (Walker et al., 2003). As the sustainability concept is related to future, good planning for strong sustainability should be operationalized for conditions of uncertainty (Baumgärtner & Quaas, 2009). This is considered as another area lacking adequate research, because sustainability performance assessment has so far not taken in account the conditions of uncertainty in previous models. Thus, the assessment outcome might not give a correct result to be utilized by decision makers in achieving optimal decision. Accordingly, a high degree of uncertainty makes a project appears risky, affecting the desire to invest, the timing of the investment, and the return on investment. In this context, the uncertainty affects the desire to implement a sustainable development strategy, when there is confusion about how environmentally beneficial, economically feasible and socially advantageous the outcomes will be. A numbers of recently published studies have shown the importance of conducting research to overcome this dilemma. Koo and Ariaratnam (2008) suggested that future research into sustainability assessment of infrastructure projects should reduce the uncertainties involved in the subjective judgments. In addition, Jeon (2007) stated that it may be worth exploring non-deterministic models to effectively reflect upon the uncertainties inherent in human decision making due to a lack of information or constraints in human thinking. Hence, handling or minimizing uncertainty in sustainability assessment will lead to improving the outcome of the assessment process.

ROLE OF LIFE CYCLE APPROACH IN SUSTAINABILITY

The importance of adapting the life cycle approach (LCA) to sustainability assessment of an infrastructure system is clear, as the systems approach recognizes and avoids trade-offs. By using the LCA in sustainability assessment, the whole life of the CSI can be assessed. Kurup et al. (2005) emphasized that the economic, social and environmental implications are required to be considered for each stage of the system life cycle. Therefore, the sustainability performance can be recognised in different system life cycle's phases. In addition, this approach helps to avoid shifting the problem from one phase into a future phase, as recognition of inter-generation fairness (Kloepffer, 2008).

While the LCA has many benefits, and is widely used, it also has limitations. The ISO 14040 (1997) has listed the following limitations to the LCA framework: subjective choices are included (e.g. system boundaries, selection of data sources and impact categories); models used in inventory and impact assessment are limited (e.g. linear instead of non-linear); local conditions may not be adequately represented by regional or global conditions; the accuracy of the study may be limited by restricted accessibility to relevant available data; and a lack of spatial and temporal dimensions introduces uncertainty in the impact assessment. Other weaknesses include its complexity, difficulty in obtaining usable results, risk of biased use, and the amount of required data being too large (Chevalier et al., 2002). In the sustainability context, another challenge relates to integrating the environmental, economic, and social dimensions into a life cycle framework with respect to clarifying the boundaries between the related impacts (Hauschild et al., 2005; Hunkeler et al., 2002; Klöpffer, 2003). To overcome these research omissions, there is a clear need for a framework to be developed especially for CIS. This framework should be able to provide answers to the research questions listed in the following section.

METHODOLOGY

The above literature review guided the development of the following overarching research question: How to objectively assess the sustainability for any type of CIS, over its life cycle, at two different levels (the system itself and its neighbourhood) during the inception stage, considering:

- System Characteristics
 - What are the sustainability dimensions that need to be considered for a particular CIS?
 - What are the sustainability indicators for each dimension, and how relevant are they to the CIS under investigation?
 - How will the temporal inter-relationship(s) between the different life cycle phases for the CIS be considered?
- Complexity
 - How to identify any causal relationships that might exist among the different sustainability indicators?
 - How to realistically model the relationships identified among the different indicators, in order to capture their overall impact on the sustainability of the CIS?

- Uncertainty
 - How to effectively overcome the uncertainty and subjectivity inherent in the decision-making process due to the lack of information, or constraints in human thinking?

The above questions led to the adoption of a research methodology that commences with the selection of sustainability indicators for each one of the four aspects of sustainability as shown in Figure 1. This is to be followed by modelling the interaction among the select indicators using fuzzy cognitive maps. Finally, fuzzy set theory will be employed to handle the uncertainty associated with quantifying the indicators.

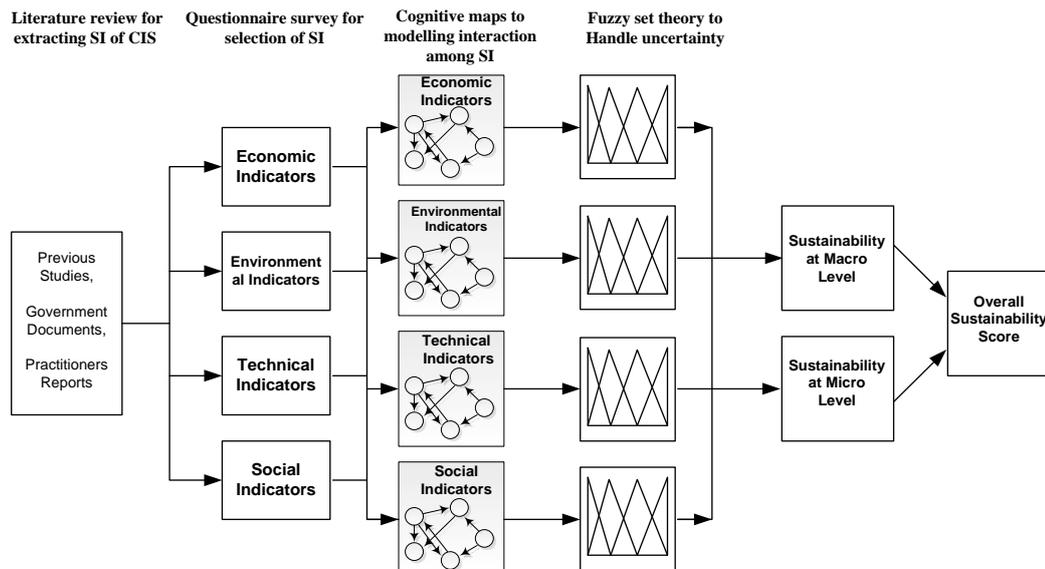


Figure 1 Research methodology framework

Questionnaire Survey

The first step is to select the sustainability indicators (SI) that are most relevant to CIS as seen by the CIS stakeholders. For this purpose, a questionnaire survey was used as a research instrument to collect data related to indicators' level of importance and frequency of use. The list of SI under consideration was derived from an extensive literature review of published materials in academic and practitioner journals. The data collected will be used to produce a short list of SI to be later utilized to construct fuzzy cognitive maps as described in the following step.

Fuzzy Cognitive Maps (FCM)

Fuzzy Cognitive Maps (FCM) is a modelling methodology for complex systems, derived from the combines of two methodologies namely fuzzy set theory and neural networks (Xirogiannis & Glykas, 2004). A typical FCM is developed by human experts who operate, supervise, or know the system and how it behaves under different circumstances (Kosko, 1992). The graphical illustration of a typical FCM is a signed fuzzy graph with feedback, consisting of nodes and weighted interconnections. The nodes of the graph are the concepts that correspond to variables, states, factors and other characteristics incorporated in the model, which are used to describe main behavioural characteristics of the system. Directed, signed and weighted arcs, which represent the causal relationships that exist among concepts, interconnect the FCM concepts. Each concept is characterized by a numeric value that represents a quantitative measure of the concept's presence in the model. A high numeric value

indicates the strong presence of a concept. The numeric value results from the transformation of the real value of the system's variable, for which this concept stands, to the interval [0,1]. All the values in the graph are fuzzy, so weights of the arcs are described with linguistic values that can be defuzzified and transformed to the interval [-1,1] (Kosko, 1986).

Measuring CIS sustainability is a complex process. The capability and effectiveness of FCM in modelling complex systems is well documented (Stylios & Groumpos, 2002). Besides, Zhang, et al. (2003) developed a new way to using FCM in case of dealing with many concepts or complex relations, the new methodology is called Quotient FCM which has higher capability of handling of complex issue than the normal FCM. Furthermore, over the past 10 years or so, FCM has been widely used and applied in different engineering research fields for a variety of problems. It has been used by Dissanayake and AbouRizk (2007) to qualitatively model and control complex construction performance related problems. Sadiq et al. (2004a) utilized FCM in developing a framework for measuring risks related to water quality failures in the distribution networks because of the ageing mains. Hobbs et al. (2002) used FCM as a tool for defining management objectives for the Lake Erie ecosystem, while later Chandana et al. (2007) used FCM to model disaster management reconstruction. However, there is no study yet that has utilized the Quotient FCM to modeling the interaction among sustainability indicators as suggested by this research.

Construction of Fuzzy Cognitive Maps

This research adopts a system theory perspective in dealing with the complexity of SI that represents the four aspects of sustainability. Hence, a complicated sustainability system for CIS is divided into four subsystems representing technical, economic, environmental, and social aspects. Also, those aspects themselves have been divided into two groups which are the micro (CIS itself), and the macro (CIS's neighbourhood) levels, as can be seen in figure 2. At the system level, FCM are proposed for modelling the interactions among sustainability indicators, which would lead to quantifying sustainability performance. At the neighbourhood level, however, the FCM will be employed to predict sustainability performance at the macro level.

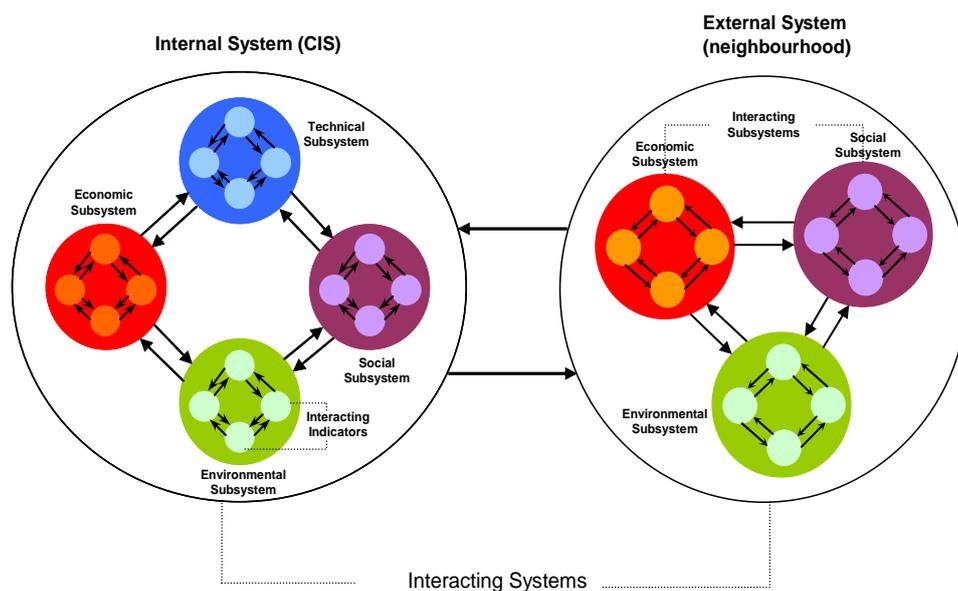


Figure 2 Sustainability indicators interaction model

CONCLUSION

There appears to be general consensus in the construction industry and research community that the way infrastructure sustainability gets assessed could be substantially improved. This paper has sought to present the limitations and shortcomings associated with existing sustainability assessment frameworks and models. In so doing, the paper presented a review of the sustainability concept of CIS at the macro and micro levels. The paper reviewed relevant and recent literature that advocates the need for a framework that could be used to assess CIS sustainability considering: 1) interactions among the four aspects of sustainability rather than dealing with them separately, 2) uncertainty associated with the sustainability indicators and their assessment by different project stakeholders, 3) the different phases of the CIS life-cycle, and 4) CIS sustainability at both the micro and macro levels. The methodology proposed allows for dealing with all of those identified issues by utilising the fuzzy cognitive mapping technique to handle the complexity and the uncertainty that is inherited in the sustainability assessment. The paper presented the research rationale, conceptual research framework and proposed methodology. Detailed analysis and modelling is being developed as part of this ongoing research, and it is envisaged that once the model has been validated in a CIS environment, then a more appropriate system sustainability assessment could be performed.

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