Automation in Construction 15 (2006) 239 – 251
AUTOMATION IN CONSTRUCTION
www.elsevier.com/locate/autcon

# Sustainability appraisal in infrastructure projects (SUSAIP) Part 1. Development of indicators and computational methods

O.O. Ugwu [a,*], M.M. Kumaraswamy [a], A. Wong [b], S.T. Ng [a]

[a]Centre for Infrastructure and Construction Industry Development (CICID), Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong
[b]Ove Arup and Partners Hong Kong, Limited

Accepted 6 May 2005

**Abstract**

The process of translating strategic sustainability objectives into concrete action at project-specific levels is a difficult task. The multi-dimensional perspectives of sustainability such as economy, society, environment, combined with a lack of structured methodology and information at various hierarchical levels, further exacerbate the problem. This paper (Part 1 of a two-part series) proposes an analytical decision model and a structured methodology for sustainability appraisal in infrastructure projects. The paper uses the 'weighted sum model' technique in multi-criteria decision analysis (MCDA) and the 'additive utility model' in analytical hierarchical process (AHP) for multi-criteria decision making, to develop the model from first principles. It discusses the development of key performance indicators encapsulated within the analytical model. It concludes by discussing other potential applications of the proposed model and methodology for process automation as part of integrated sustainability appraisal in infrastructure design and construction. Part 2 uses a case study to demonstrate the model application in infrastructure sustainability appraisal at design stages. The paper also discusses the challenges for sustainability research, and gives recommendations.


*Keywords:* Sustainability index; Multi-criteria decision analysis (MCDA); Weighted sum model; Reasoning map; Utility model; Key performance indicators; Design for sustainability

## 1. Introduction and motivation for research

Sustainable development as a concept has been gaining increasing popularity across various sectors including the construction industry, since the Brundtland Commission Report in 1987 [1]. Various national governments have set up programmes in order to meet the objectives outlined following the Rio de Janeiro Summit in June 1992. The Rio summit culminated in resolutions such as the *Rio Declarations on Environment and Agenda 21* [2], and was followed by the South African summit in 2002 [3]. However, the process of translating national strategic sustainability objectives into concrete action at micro (i.e., project-specific)-levels is a difficult task. Inadequate understanding of the interactions and cumulative impacts of the various sub-level sustainability indicators further compound the difficulty in sustainability appraisal of designs. Thus, although there is increasing realisation of the need to design and construct for sustainability, the real challenge is on achieving these objectives at the micro-level.

Given the international focus on sustainability in recent years, there is a dire need for methods and techniques that would facilitate sustainability assessment and decision making at the various project level interfaces (i.e., from conceptualisation to design, construction, operation and decommissioning). However, review of literature shows that the current focus is on strategic policy formulation levels. Examples of such macro-level policy-driven strategies can be found in the literature [8,9,22–24,26]. Thus, while current sustainability initiatives, strategies, framework and processes focus on wider national aspirations and strategic

* Corresponding author. Tel.: +852 2857 8555; fax: +852 2559 5337.
*E-mail address:* oougwu@hkucc.hku.hk (O.O. Ugwu).

0926-5805/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.autcon.2005.05.006

objectives, they are noticeably weak in addressing micro-level integrated decision making. Paradoxically, it is precisely at the micro-levels that national strategic objectives have to be translated into concrete practical actions, by using a holistic approach to facilitate decision making.

In practice, designers have traditionally relied on past experiences and their intuition, in making decisions on new project design configurations. This is because of a lack of integrated structured methodology and techniques for sustainability appraisal as part of infrastructure delivery (especially during design and construction). Such decisions are often predicated on their mental models of past projects, some of which may have been designed with very little or no consideration to sustainability issues. This approach will be referred to as *metaphorical-based design*. Although such metaphorical-based designs offer quick and easy solutions, they often stifle innovation (and even militate against the natural spirit of enquiry and experimentation), since decisions are simply based on tried alternatives that have worked in the past, but were not necessarily the most sustainable solution.

The difficulty in addressing national strategic sustainability objectives such as economy, society, environment etc. in an integrated holistic manner is further exacerbated by the high aggregation of these objectives for micro-level decision making. As an illustration, 'economy' as a sustainability indicator encapsulates sub-elements such as direct/indirect costs (which further subsumes construction/operation costs), and other life cycle cost elements. Similarly, 'environment' subsumes other sub-elements such as land use, water, air, noise, ecology, waste management, all of which are further subdivided into other finite sub-categories. Resource utilization includes indicators such as constructability, material availability and reusability among others. Moreover, there is complex interaction between these variables in project design and specification. Sections 4 and 5 discuss details of the indicators at various sub-levels. On the other hand, designers are imbued with generic tacit knowledge, which needs to be adequately harnessed, managed and deployed for use in collaborative design and specifications, as part of strategic organisational corporate knowledge management.

The main challenge is how designers can evaluate a given design option by aggregating its performance along various sustainability indicators. Such design evaluation and appraisal would contribute to making better sustainability-driven decisions at the project levels. However, review of available literature indicates significant gaps in sustainability research. The major gap is to investigate how to guide designers and other stakeholders to translate strategic macro-level sustainability objectives into practical actions as part of the infrastructure delivery processes at the micro-level (i.e., design and construction) [5,6]. This paper is envisaged to make a substantial contribution by addressing this identified research gap. It presents a methodology and computational processes (analytical models) that address the existing problem of designing for sustainability in infrastructure systems delivery in the Architecture/Engineering/Construction (AEC) sector. The methodology and analytical model were validated using a mega-infrastructure project as a case study [48].

## 2. Research question and methodology—need for sustainability assessment strategy

The main design problem that drive the research questions and issues investigated, is anchored in the following question: 'how can a designer generate and evaluate design options and choose a set of design construction specifications to effectively implement national sustainability strategies and objectives at the infrastructure project level?' The research framework and methodology consisted of the following key stages: (i) review of existing literature, (ii) development and validation of key performance indicators (KPI) using various instruments such as survey and interviews with stakeholders, (iii) developing a structured methodology and formulating an analytical model for the multi-criteria decision-making problem domain, and (iv) application in a case study mega-infrastructure project using a PC-based spreadsheet application (discussed in Part 2 [48]).

There are several dictionary definitions of the word *strategy* most of which relate to military planning and operations. However, two related definitions considered contextually suitable for the purpose of this paper define it as "a plan of action or policy to achieve something" [11], and "skilful management in attaining an end . . . the method of conducting operations. . ." [12]. These definitions indicate that there are several key elements required to develop effective strategies for sustainable construction environment. Three of these critical elements include (i) clear formulation and setting of objectives; (ii) identifying and evaluating alternatives in quantitative and/or qualitative terms; and (iii) effective implementation of a selected/chosen alternative. In the broader context of sustainability of infrastructure systems, which is the focus of this paper, the strategic objectives are articulated at the macro-level to underpin national frameworks for achieving broader sustainable development including sustainable construction environment. The alternatives in (ii) are design options, while the implementation in (iii) translates to choosing appropriate construction methods and techniques including effective management processes to transform abstract designs, concepts, and specifications into concrete sustainable physical artefacts.

## 3. Review of sustainability and related research

### 3.1. Infrastructure development and sustainable construction environment

Infrastructure projects have significant impact on a sustainable construction environment. Civil engineering