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

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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.

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
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 infra-

structure 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
infrastructure differs from other structures such as buildings for which there are tools developed for sustainability assessment. The differences include diversity in the nature of projects, variety in design standards, construction practice and operational requirements, great impact on urban and overall project management mostly because of the large zones of influence (including ecological, social, natural etc.), and extensive variation in contract types and procurement methods. This section reviews current sustainability research.

3.2. Current sustainability research

Current research on sustainability assessment methods has focused mainly on environmental protection. A review conducted using the BEQUEST (Built Environment Quality Evaluation for Sustainability through Time) framework showed that there are several methods available for sustainability assessment of urban activities. However, the methods and decision aids/tools development have focused mainly on buildings [27–29]. The review also showed that while many of the methods are recent developments, they remain essentially experimental and have not yet been widely adapted in practice. Moreover, while there exist several research initiatives addressing different dimensions of urban sustainability including macro-level policy planning and programme design development, there is noticeably poor coverage of construction and operations [30–32]. The same observation holds for infrastructure projects where current focus is largely on macro-level policy planning, with little research focusing on the micro-level design and construction stages.

Several researches have been initiated to investigate different topics related to sustainability and environment in general. Some of the areas discussed in literature include environment and industrial ecology [36,49–51]. Industrial ecology approach involves the analysis of flow of materials, energy, capital, labour and information within production and consumption systems. It considers the environmental impacts of these variables over the product whole life cycle. Other related researches include group decision making [36,37], life cycle cost analysis [40], multi-criteria decision analysis (MCDA) [38,39], and environmental management systems and tools [10,27,28]. The European Union has the European Environmental Agency (EEA) that is responsible for developing and applying a comprehensive approach to ensure all important aspects and interacting factors influencing sustainability are analysed [52]. Some research investigated social dimensions and partnership [34,35], risk analysis in environmental decision making [38–40] multi-criteria decision analysis applications in designing for environment and other forms of selection appraisal problems [40–46]. The outlined literature indicates growing interest in research on environment and sustainability. However, the work reported in this paper draws from existing literature but focuses on investigating a holistic and integrative (i.e., the decision makers handle certain human-oriented aspects of the complex decision-making problem at different organisational hierarchical levels) approach to assess the sustainability of infrastructure projects at various stages in the project life cycle. This includes developing the micro-level indicators required for sustainable assessment at project level, formulating underpinning mathematical models and assessment methods for quantitative analysis.

4. Key performance indicators (KPIs) for sustainable infrastructure delivery

A prerequisite to project-level sustainability appraisal is to develop the indicators with the stakeholders involved in infrastructure project delivery. In general such indicators are useful for monitoring progress, understanding sustainability, educating all the stakeholders involved in the process, like consultants, clients, contractors, suppliers etc., on the issues, describing linkages between the indicators (for example using causal maps or interaction matrix tables), motivating and focusing action. Another requirement in indicators development is that they be quantifiable and effective. Other basic characteristics of an indicator include (i) relevance—it must be relevant, and fit the purpose for performance measurement, (ii) understandable—it should be easily understandable to all present and future users. This means that there has to be shared common understanding of terms and definition of the indicators (i.e., ontology), without loss of meaning; and (iii) it must be usable by the community (stakeholders).

Also since the ultimate aim of any sustainability indicator development is for it to be applied to real situations, this means that usability by the community should be an underpinning principle in the indicator development. Usability also highlights the fact that the indicator should be specific to the type of project domain and community to which it will be applied. This means that indicators for use in sustainability appraisal of infrastructure projects should be chosen to suit the characteristics of civil projects. A corollary here is that indicators used for building structures may not be fully compatible with assessing civil engineering infrastructure projects, since such indicators are project-specific. The next section discusses the development of sustainability indicators for infrastructure projects. This required validation with industry stakeholders.

4.1. Survey instruments and methodology

The research was conducted using a combination of structured interviews with industry professionals, case study project data, existing government guidelines on environmental impact assessments and sustainable construction environment, literature on sustainability research, and questionnaire-based survey for indicator validation. Fig. 1 captures the methodology for indicators development.
The survey was conducted over a 1.5-month period from 1 August to 15 September 2003. A total of 134 questionnaires were sent to senior personnel in consultant, client, contractor and supplier organisations in Hong Kong. In order to achieve the above outlined objectives, the questionnaire was divided into two parts. The questionnaire was very detailed and outlined the specific contexts of the research to the respondents. Part I elicited respondents’ background information (i.e., demographic data), while Part II focused on obtaining ideas on the suitability of various proposed sustainability indicators for use in assessing infrastructure projects. The questionnaires were distributed using a combination of post, internal circulation through contact persons working in the identified companies, fax, and by email.

In Part I, personal background questions include information on respondent’s awareness of sustainability appraisal instruments such as Global Reporting Initiative (GRI) and United Nations Commission on Sustainable Development (UNCSD), and the level of use of such programs in practice. It revealed that although sustainability has been widely addressed in Hong Kong over the past 10 years, systematic appraisal tools are still not popular in practice. Personal background information elicited also include the respondent’s experience and participation in sustainability-driven infrastructure project(s). Part II of the questionnaire asked respondents to give a score from 1 to 5 against each of the selected indicators to determine their suitability in assessing sustainability of typical infrastructure projects. This translates as follows on the Likert scale: 1 = not suitable, 5 = very suitable, with 3 being the average value for acceptance of an indicator suitability.

A total of 33 valid questionnaires were returned, giving a response rate of approximately 24.6%. Clients and Consultants gave higher response rates. This could be because they are generally the people who make design decisions and are, therefore, mostly confronted with the realities of making judgment on the sustainability of projects. Two invalid responses were also received from a contractor and a supplier company, who both left Part II blank. Interestingly, they noted that they are not in a suitable position in the field to make judgment on whether a design decision is “sustainable” or not, and further commented that it should be client, consultants or end-users’ responsibility. However, this raises significant issues on sharing joint responsibility for infrastructure sustainability. Table 1 summarises key demographic information on the respondents.

### 4.2. Analysis of the survey results—indicator rankings

This section uses descriptive statistics to discuss the results of the questionnaire-based indicators validation. Table 2 shows the mean scores (out of maximum score of 5) for the proposed indicators. It reflects the stakeholders’ perceptions and cumulative ranking. Table 3 summarises the respective top 25 indicators ranked by the various stakeholders and maps these into main category indicators:

![Fig. 1. Research framework and methodology.](image-url)

| Table 1 | Summary of respondents’ demographic data (source: analysis of survey data) |
|---------|-------------------------------------------------------------------------|
| **Panel a: Type of organisation** | **Panel b: Involvement in sustainability-driven projects** |
| Client (public and private sector) | 14 | Yes: Involved in projects | 13 (39.4%) |
| Consultants | 14 | No: Not involved | 20 (60.6%) |
| Contractors | 5 | | |

| **Panel c: Awareness of tools and sustainability initiatives** | **Panel d: Experience in using sustainability appraisal tools** |
|---------------------------------------------------------------|---------------------------------------------------------------|
| GRI (Global Reporting Initiative) | Used sustainability appraisal tools | 7 (21.2%) |
| UNCSD (United Nations Commission for Sustainability Development) | Not used sustainability appraisal tool | 26 (78.8%) |
Table 2
Stakeholders’ perception of KPIs in infrastructure sustainability (source: analysis of survey data)

| Indicator name (Level 4) | Key sustainability item (Level 2) | Sustainability sub-item (Level 3) | Suitability assessment<sup>b</sup> | Public and private clients N=14 mean (SD, rank) | Consultants N=14 mean (SD, rank) | Contractors N=5 mean (SD, rank) |
|--------------------------|----------------------------------|----------------------------------|----------------------------------|-----------------------------------------------|---------------------------------|-------------------------------|
| Reusability of moulds, formwork etc. | Resource utilization | Reusability | 4.19 (0.78, 1) | 4.14 (0.77, 6) | 4.38 (0.77, 1) | 3.80 (0.84, 6) |
| Safety                 | Health and safety                | Public                          | 4.16 (0.85, 2) | 4.21 (0.97, 5) | 4.31 (0.75, 3) | 3.60 (0.55, 16) |
| Health                 | Health and safety                | Public                          | 4.13 (0.91, 3) | 4.29 (1.14, 3) | 4.08 (0.76, 14) | 3.80 (0.45, 6) |
| Long-term health (e.g., respiratory duct disease, permanent deafness etc.) | Health and safety | Occupational | 4.09 (0.86,4) | 4.14 (0.95, 8) | 4.23 (0.83, 5) | 3.60 (0.55, 16) |
| Impact as to assessment under EIAO | Environment | Water                           | 4.00 (0.84, 5) | 4.29 (0.83,1) | 4.08 (0.76, 14) | 3.00 (0.00, 47) |
| Impact as to assessment under EIAO | Environment | Ecology                         | 4.00 (1.00, 6) | 4.23 (1.01, 4) | 4.08 (0.95, 16) | 3.20 (0.84, 39) |
| Extent of loss of habitat or feeding grounds | Environment | Land use                         | 4.00 (1.02,7) | 4.14 (1.10, 9) | 4.23 (0.83, 5) | 3.00 (0.71, 48) |
| Solid—construction material | Environment | Waste management                 | 3.97 (0.86, 8) | 3.93 (1.00, 13) | 4.15 (0.80, 10) | 3.60 (0.55, 16) |
| Liquid waste—toxic      | Environment | Waste management                 | 3.97 (1.00, 9) | 3.79 (1.19, 22) | 4.38 (0.77, 1) | 3.40 (0.55, 16) |
| Life cycle cost         | Economy                            | Direct cost                     | 3.97 (1.12, 10) | 3.79 (1.25, 23) | 4.15 (1.14, 12) | 4.00 (0.71, 1) |
| Ventilation design—service stage | Environment | Air                             | 3.97 (0.84, 11) | 3.93 (1.38, 16) | 4.08 (0.64, 13) | 3.75 (0.96, 15) |
| Impact as to assessment under EIAO | Environment | Air                             | 3.94 (0.91, 12) | 4.29 (0.91, 2) | 3.92 (0.76, 20) | 3.00 (0.71, 47) |
| Inclusion of sustainability-related clauses | Project administration | Contract                       | 3.91 (0.82, 13) | 4.07 (0.62, 10) | 3.92 (0.86, 24) | 3.40 (1.14, 34) |
| Safety                 | Health and safety                | Occupational                    | 3.91 (1.06, 14) | 3.93 (1.38, 16) | 3.92 (0.76, 20) | 3.40 (0.84, 9)  |
| Innovative material    | Resource utilization             | Type                            | 3.88 (0.66, 15) | 3.79 (0.70, 18) | 4.00 (0.71, 18) | 3.80 (0.45, 6)  |
| Extent of tree felling  | Environment | Land use                         | 3.88 (0.87, 16) | 4.14 (0.77, 6) | 3.77 (0.83, 30) | 3.40 (1.14, 34) |
| Design flexibility towards noise reduction measures | Environment | Noise                           | 3.84 (0.68, 17) | 3.79 (0.70, 18) | 3.85 (0.69, 26) | 4.00 (0.71, 1)  |
| Solid—dredged/excavated material | Environment | Waste management                 | 3.84 (0.85, 18) | 3.57 (0.94, 30) | 4.15 (0.80, 10) | 4.00 (0.71, 1)  |
| Extent of encroachment upon concerned areas | Societal | Cultural Heritage               | 3.84 (0.85, 18) | 3.79 (0.97, 21) | 4.00 (0.71, 18) | 3.80 (0.45, 6)  |
| Prefabricated material  | Resource utilization             | Type                            | 3.84 (0.85, 18) | 3.50 (1.09, 35) | 4.15 (0.38, 8) | 3.60 (0.89, 22) |
| Reprovision of habitat  | Environment | Ecology                         | 3.84 (1.02, 21) | 3.71 (1.14, 28) | 4.23 (0.83, 5) | 3.20 (0.84, 39) |
| Construction material   | Resource utilization             | Material availability           | 3.84 (1.00, 22) | 3.31 (1.11, 43) | 4.31 (0.75, 3) | 4.00 (0.71, 1)  |
| Footprint of project in archaeological site | Societal | Cultural heritage               | 3.78 (0.79, 23) | 3.93 (0.83, 12) | 3.85 (0.80, 27) | 3.20 (0.45, 36) |
| Short-term health (e.g., spread of diseases, cleanliness of site etc.) | Health and safety | Occupational | 3.78 (0.87, 24) | 3.71 (1.07, 25) | 3.92 (0.76, 20) | 3.60 (0.55, 16) |
| Water reuse             | Environment | Water                           | 3.78 (0.87, 24) | 3.93 (1.07, 15) | 3.77 (0.73, 29) | 3.40 (0.55, 25) |
| Impact as to assessment under EIAO | Environment | Noise                           | 3.78 (1.24, 26) | 4.00 (1.52, 11) | 3.77 (1.09, 33) | 3.20 (0.45, 36) |
| Harmony with surrounding environment | Environment | Visual impact                  | 3.75 (0.95, 27) | 3.71 (1.07, 25) | 3.85 (0.80, 27) | 3.60 (1.14, 24) |
| Early contractors’ involvement (ECI) | Resource utilization | Constructability             | 3.71 (0.82, 28) | 3.38 (0.87, 38) | 4.15 (0.69, 9) | 3.40 (0.55, 25) |
| Those associated/ complementary with the chosen materials | Resource utilization | Material availability       | 3.69 (0.82, 29) | 3.36 (0.93, 39) | 4.00 (0.58, 17) | 3.80 (0.84, 9)  |
| Impact as to assessment under EIAO | Environment | Visual impact                  | 3.68 (1.08, 30) | 3.85 (1.21, 17) | 3.77 (1.01, 32) | 3.00 (0.71, 48) |
| Scrap value after decommissioning | Resource utilization | Reusability                     | 3.66 (0.79, 31) | 3.79 (0.70, 18) | 3.77 (0.83, 30) | 3.00 (0.71, 48) |
| Ventilation design—during construction | Environment | Air                           | 3.63 (0.83, 32) | 3.71 (0.91, 24) | 3.62 (0.77, 37) | 3.40 (0.89, 32) |
| Early suppliers’ involvement (ESI) | Resource utilization | Constructability      | 3.59 (0.95, 33) | 3.29 (0.99, 44) | 3.92 (0.95, 25) | 3.60 (0.55, 16) |
| Rehabilitating cost of ecosystem | Economy | Indirect cost | 3.59 (1.07, 34) | 3.71 (1.07, 25) | 3.69 (1.18, 36) | 3.00 (0.71, 48) |

(continued on next page)
### Table 2 (continued)

| Indicator name (Level 4*) | Key sustainability item (Level 2) | Sustainability sub-item (Level 3) | Suitability assessmentb<br>All N=33 mean<br>(SD, rank) | Public and private clients N=14 mean<br>(SD, rank) | Consultants N=14 mean<br>(SD, rank) | Contractors N=5 mean<br>(SD, rank) |
|-------------------------|---------------------------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Liquid waste—non-toxic | Environment                      | Waste management                | 3.56 (0.88, 35)                 | 3.36 (1.01, 41)                 | 3.92 (0.76, 20)                 | 3.40 (0.55, 25)                 |
| Extent of land acquisition | Environment                      | Land use                        | 3.56 (0.88, 35)                 | 3.64 (1.08, 29)                 | 3.54 (0.78, 42)                 | 3.20 (0.45, 36)                 |
| View from District Councils | Societal                         | Public perception                | 3.56 (1.01, 37)                 | 3.57 (0.94, 30)                 | 3.46 (1.20, 48)                 | 3.80 (0.84, 9)                  |
| Route(s) for waste disposal | Resource utilization              | Site access                     | 3.53 (0.92, 38)                 | 3.29 (1.07, 45)                 | 3.69 (0.75, 34)                 | 3.80 (0.84, 9)                  |
| Approach/Criterion towards contractors | Project administration          | Procurement method              | 3.53 (1.02, 39)                 | 3.50 (1.02, 33)                 | 3.62 (1.12, 39)                 | 3.40 (0.89, 32)                 |
| Ease of quality control | Resource utilization              | Quality assurance                | 3.52 (0.96, 40)                 | 3.54 (1.05, 32)                 | 3.46 (0.97, 45)                 | 3.60 (0.89, 23)                 |
| Complaints from local parties/villages | Societal                        | Cultural Heritage                | 3.47 (0.88, 41)                 | 3.43 (0.65, 36)                 | 3.62 (1.12, 39)                 | 3.20 (0.84, 39)                 |
| Amount of paperwork | Project administration            | Contract                        | 3.44 (0.95, 42)                 | 3.43 (1.09, 37)                 | 3.54 (0.88, 43)                 | 3.20 (0.84, 39)                 |
| Air outlet design | Environment                      | Air                             | 3.44 (0.95, 42)                 | 3.36 (1.01, 41)                 | 3.62 (0.96, 38)                 | 3.20 (0.84, 39)                 |
| Route(s) for construction traffic | Resource utilization | Site access                     | 3.41 (0.98, 44)                 | 3.14 (1.17, 53)                 | 3.46 (0.78, 44)                 | 4.00 (0.71, 1)                  |
| Connectivity with hinterland | Environment                     | Land use                        | 3.38 (0.98, 45)                 | 3.21 (1.05, 47)                 | 3.69 (0.95, 35)                 | 3.00 (0.71, 48)                 |
| Extent of blockage | Societal                         | Public access                   | 3.34 (0.79, 46)                 | 3.50 (1.02, 33)                 | 3.15 (0.55, 52)                 | 3.40 (0.55, 25)                 |
| Resettling cost of people | Economy                          | Indirect cost                   | 3.34 (0.94, 47)                 | 3.07 (0.83, 54)                 | 3.46 (1.05, 47)                 | 3.80 (0.84, 9)                  |
| Approach/Criterion towards suppliers | Project Administration            | Procurement method              | 3.34 (1.07, 48)                 | 3.14 (1.10, 52)                 | 3.62 (1.12, 39)                 | 3.20 (0.84, 39)                 |
| Type of contract | Project administration            | Contract                        | 3.31 (1.00, 49)                 | 3.21 (1.05, 47)                 | 3.46 (0.97, 45)                 | 3.20 (1.10, 46)                 |
| Extent of diversion | Societal                         | Public Access                   | 3.28 (0.81, 50)                 | 3.21 (1.05, 47)                 | 3.31 (0.63, 50)                 | 3.40 (0.55, 25)                 |
| Adverse impact on tourism values | Economy                          | Indirect cost                   | 3.25 (0.95, 51)                 | 3.36 (0.93, 39)                 | 3.38 (1.04, 49)                 | 2.60 (0.55, 54)                 |
| Employment of labour | Economy                          | Indirect cost                   | 3.16 (0.95, 52)                 | 3.14 (1.03, 51)                 | 3.08 (1.04, 53)                 | 3.40 (0.55, 25)                 |
| Initial cost | Economy                          | Direct cost                     | 3.16 (0.99, 53)                 | 3.21 (0.89, 46)                 | 2.92 (1.19, 55)                 | 3.60 (0.55, 16)                 |
| View from ACABASd | Environment                      | Visual impact                   | 3.10 (0.98, 54)                 | 3.15 (0.99, 50)                 | 3.00 (1.08, 54)                 | 3.20 (0.84, 39)                 |
| Fung Shui* | Societal                         | Public perception                | 3.00 (0.98, 55)                 | 2.86 (0.77, 55)                 | 3.31 (91.18, 51)                | 2.60 (0.89, 55)                 |

*a Level 1 refers to the generic level of infrastructure project sustainability. Section 5.3 discusses the hierarchical classification and reasoning map in detail.

*b Clients rankings are deemed very critical because it reflects the wider macro-level sustainability goals. Public clients in particular are deemed to factor in the national agenda and wider ‘public opinion’ in their response. Project delivery is all about listening to the voice of the client. Closer examination of Table 1 shows that top 25 ranked indicators have a minimum mean score of 3.71 (for rehabilitation cost of ecosystem, which is ranked 34 by all stakeholders. Table 3 summarises the respective top 25 ranked indicators by all the stakeholders.

c EIAO—Environmental Impact Assessment Ordinance (in HKSAR), or equivalent statutory provisions in a given country.

d ACABAS—Advisory Committee on Aesthetics of Bridges and Associated Structures (in HKSAR), or its equivalent body in a given country/state. The activities of ACABAS in HKSAR are intended primarily towards vetting the design of bridges and other structures associated with the public highway system from the aesthetic and visual impact points of view.

e This is a metaphysical belief that is deeply rooted in Chinese tradition and culture. It is similar to the concept of ‘Ubuntu’ in South Africa [25,33].

Environment, health and safety, economy, societal, resource utilization, and project administration. The minimum mean values for the top 25 indicators for the various stakeholders are, respectively, Clients (3.71), Consultant (3.92), and Contractors (3.40). Consultants generally gave higher ratings to the indicators.

The next section discusses some of the findings under the different main indicators.

**Environment:** Clients have 13 indicators in this category among their top 25 rankings. Also clients show particular preference for indicators that are measured by their compliance with statutory and regulatory provisions such as the EIAO. This reflects the existing approach to enforcing responsible sustainability behaviours. This is predominantly through command and control structures manifested in the form of ordinances and statutory guidelines as opposed to responsible behaviours induced by market forces. Other indicators that clients rank high are performance-based and relate to waste management.

**Health and safety:** All the stakeholders rank indicators under this main category high. It is of particular interest that public health-related indicators scored very good ranking. Three of the indicators are within the top 4 positions in the overall ranking by all stakeholders (Table 2). This observation is in contrast with what was obtainable in Hong Kong before March 2003. Within this period, health and safety was not accorded such very high priority. The questionnaire survey for indicators validation was conducted between August and September 2003. This was within few months after the Severe Acute Respiratory Syndrome (SARS) outbreaks in mainland China and Hong Kong that occurred from March 2003 to June 2003. However, this ranking and observation is confirmed by the Sustainable Development Unit (SDU) in HKSAR which noted that [24]:

“Stakeholders have often accorded weight to different (sustainability) areas depending on prevailing problems in society. For example, in 2001–2002, the question of...
sustainable health and hygiene was rarely mentioned in (SDUs) liaison meetings with stakeholders, and was not one of the priorities. Yet in recent liaison meetings (after the SARS outbreak) this has been cited as a key pillar of sustainable development in Hong Kong.”

This observation, which is also substantiated by the SDU, shows that some indicators like health and safety are vulnerable to shifts in society’s definition of sustainability and prioritization of the core elements. It further raises some issues related to intergenerational priorities in sustainability and hence the associated risks. Thus, there is need for sustainability risk management strategies.

Economy: All the stakeholders rank life cycle cost on the top 25, but there are noticeable differences in the rankings. Clients rank it 23, while consultants rank it 12 and the contractors rank it 1. It is also observed that contractors rank four cost-related indicators on their top 25. Clients rank ‘rehabilitation cost of ecosystem’ as No. 10. Consultants rank ‘rehabilitation cost of ecosystem’ as No. 12. Both indicators fall under cultural heritage.

Resource utilization: All the stakeholders rank reusability of moulds among the top 10, while the cumulative ranking is No. 1 (Table 2). Generally, indicators under resource utilization relate to construction methods and strategies that minimise depletion of the limited resources. Construction is an intensive transformation process that often involves assembling and transforming resources into physical artefacts. Resource reuse relates to material conservation and hence environmental aspects of sustainability. It is also a function of construction methods and innovative designs (including designing for durability and deconstruction) etc. This ranking reflects increasing level of awareness among stakeholders and their recognition of the need to avoid overusing renewable resources. Contractors rank three indicators in this category as No. 1. Also contractors rank eleven of the indicators under this among their top 25 indicators. This is significant because contractors are mostly engaged at the construction stage of projects. They are in the best position to ensure optimised resource utilization during construction (e.g., through reuse, adequate...
quality control to ensure waste minimisation through elimination of reworks.

**Project administration:** Indicators under project administration account for the need to adopt strategies that facilitate collaborative working among project teams, as a prerequisite in achieving sustainability objectives. Both clients and consultants rank the indicator ‘inclusion of sustainability-related clauses in project specification documents’ 10 and 24 respectively. This suggests that there is awareness and/or recognition that explicit inclusion of sustainability-related clauses is an important driver towards achieving sustainable construction environment. This is because such an unambiguous inclusion commits the project stakeholders to work towards the same sustainability objectives. Such goals could be included as one of the clauses in a partnering charter, to inject sustainability responsible behaviours in the infrastructure delivery.

Table 2 (column 4) shows that the cumulative mean score of all the indicators by all the respondents is at least 3.0 out of a maximum score of 5.0. The differences in rankings in Tables 2 and 3 highlight stakeholders’ preferences on the suitability of the indicators for assessing infrastructure sustainability. However, it is evident that not all indicators are applicable to every project and in every country. Therefore, indicators to be applied should be project and country-specific, with the Project Manager or other users of the framework making decisions on the applicable indicators. Applying weightings to each project and for a given design option would take account of and reflect such project-specificity.

4.3. **Indicators suggested by stakeholders**

In addition to assessing the suitability of the proposed indicators in the SUASAIP framework, listed in the preceding section (Table 2), the respondents also suggested additional indicators, which have been taken into consideration in further development of the KPIs. Table 4 summarises the suggested indicators. Their descriptions are based on additional information given by the respective respondents that recommended their inclusion.

The suggested indicators demonstrate the need for flexibility in constructing the KPIs used in sustainability assessment. One of the respondents suggested during an interview that any proposed sustainability appraisal methodology must take into consideration the existing design practices in organisations. The implication is that indicators development should be an evolutionary process and not static.

Once the KPIs are validated with potential end users, then decision-making techniques that involve numerical analysis of discrete alternatives can be established. The next requirement is analysis to determine potential impacts of proposed design options. A decision model that encapsulates these sustainability indicator variables would enable stakeholders to consider a wide range of options (both conventional and innovative designs) before committing to a particular option.

Moreover, it is possible to automate some aspects of the computational and decision analysis process (e.g., by providing ICT-based decision aid/stools as ‘one-stop shop’ solution for integrated sustainable design [47]). A final phase/requirement of the decision-making process is analysis to determine the performance of various options using the same set of sustainability metrics (i.e., KPIs). This requires consideration of the various KPIs at sub-elemental levels. It further indicates that this is a multi-attribute decision-making problem. The requirement here is for decision-making techniques that involve numerical analysis of discrete alternatives. The ensuing section discusses computational methods for sustainability assessment. The underpinning mathematical model encapsulates the KPIs for computational analysis and decision making in infrastructure delivery (Table 2).

5. **Sustainability assessment: procedures and computational methods**

Evaluating the sustainability of different design concepts/alternatives using numerical analysis involves three main steps. The process steps include (i) determining the relevant applicable criteria and alternative design options, (ii) assigning numerical values (i.e., weights) to measure the relative importance of these criteria for a given project and
geographical location (i.e., country-specific) contexts. Each alternative is then appraised using the same basket of criteria, and (iii) processing the numerical values (i.e., computational analysis) to determine the ranking of alternative design options along the various main sustainability indicators. The ensuing section focuses on the analytical (numerical) computation of “sustainability index” using the data described in steps (i) and (ii). First the next sections describe the axiomatic assumptions made in the development and the underlying mathematical model.

5.1. Mathematical foundations—basic axiomatic assumptions and analytical model

The basic assumptions in formulating a mathematical model for infrastructure sustainability assessment include;

1. The design alternative (design option): \( D = \{D_1, D_2, \ldots, D_m\} \) represent a discrete set of possible design options.
2. The criteria (sustainability KPIs in Table 2) are known and denoted by the set: \( \mathcal{Sc} = \{\mathcal{Sc}_1, \mathcal{Sc}_2, \ldots, \mathcal{Sc}_n\} \).
3. The criteria weights are represented by a vector of scalar quantity given by: \( \mathbf{w} = (w_1, w_2, \ldots, w_n) \), where \( 0 \leq w_i \leq 1 \), \( X \) being an integer whose value is usually determined during the decision-making process.
4. A range of scalar vector defines the utility value of a design option. This is given as \( U^k = (u_{1}^k, u_{2}^k, \ldots, u_{n}^k) \), where \( u_{i}^k \) is determined by a scoring means that assigns a utility value for a given design alternative based on its comparative performance in a given KPI.
5. A vector of linguistic terms can also be mapped into a fuzzy set of utility values. For example, let \( \mathbf{L} = (l_{1}, l_{2}, \ldots, l_{n}) \) be a linguistic vector that defines some qualitative indicator such as ‘ecological impact as to assessment under EILO.’ As illustration, for a bridge pile operation, the assessment may consider mitigation measures required to prevent excavated soil from contaminating and polluting the seawater thereby impacting the wider ecosystem.

The set of linguistic terms may include: \( \mathbf{L} \) (low-level mitigation measures, \{Yes, No\}), high-level mitigation measures \{Yes, No\}). These can be mapped into equivalent scalar utility vector: \( U^k = \{(a_1, b_1), (a_2, b_2)\} \). Examples of low mitigation measures to counteract such ecological impact include the use of cofferdams and silk curtains. Thus, a scalar utility vector of the form \( U^k = \{(a_1, b_1), (a_2, b_2), (a_3, b_3), \ldots (a_n, b_n)\} \) can be further associated with a given vector of linguistic terms, where \( a_i, b_i \) represent corresponding assigned values.

6. For a given set of sustainability KPIs, the decision maker (e.g., designer) would select an applicable subset of criteria based on the location-specific considerations, as applicable to a project under consideration. This indicates a need for tool(s) that facilitate the composition (construction and deconstruction) of indicators ‘on the fly.’ Let the selected subset be defined by \( \mathcal{Sc} = \{\mathcal{Sc}_{t-1}, \mathcal{Sc}_{t-2} \ldots, \mathcal{Sc}_t\} \).

The mathematical model formulation is derived from first principles. It begins by considering infrastructure sustainability appraisal as a decision-making problem with \( M \) design alternatives, and \( N \) criteria. Each criterion can be decomposed into finite elemental levels. The convention in this research study is to denote each design alternative as \( D_i \) where \( (i = 1, 2, 3 \ldots M) \), and the sustainability criteria (indicators) as \( \mathcal{Sc}_j \) (for \( j = 1, 2, 3 \ldots N \)). It is also assumed that for each \( \mathcal{Sc}_j \), the decision maker assigns a weight \( W_j \) that lies over a defined range: \( W_j \leq K \) where \( K \) is a user-defined integer scalar quantity.

The numerical value of the weight will be determined by priorities aligned to a country’s strategies to achieve the broader objectives of sustainable environment. For example, in a country where environmental considerations have the highest priority in its sustainability agenda, designated major projects often undergo detailed environmental impact analysis and a very comprehensive environmental approval process. This often culminates in the issuance of specific environmental permit before the project commences (for example in HKSAR). For such situations, sub-criteria under environment could be assigned the maximum numerical weight and other indicators assigned less weight as appropriate for the evaluation. In mathematical terms, the measure of performance of a given alternative \( D_i \) in terms of a main sustainability criterion \( \mathcal{Sc}_j \) is given by \( d_{ij} \) (for \( i = 1, 2, 3 \ldots M; j = 1, 2, 3 \ldots N \)). The mathematical model formulation assumes that the decision maker determines the values of \( d_{ij} \). These assumptions translate the sustainability appraisal problem into a multi-criteria decision-making (MCDM) problem. This can be represented in a decision matrix table (Table 5).

Table 5 shows that given a typical table with populated data sets, and decision-making method, the sustainability appraisal problem for the designer reduce to finding the “best” alternative (design option) or to rank the various design options.

5.2. Multi-criteria decision-making—the weighted sum model for sustainability index

This section formulates the mathematical model for computing the sustainability index (SI) using the weighted

| Table 5  | Sustainability appraisal decision matrix |
|----------|------------------------------------------|
| Design   | Sustainability criteria                  |
| (Options)| \( \mathcal{Sc}_1 \) | \( \mathcal{Sc}_2 \) | \( \mathcal{Sc}_3 \) | \( \mathcal{Sc}_4 \) | \( \mathcal{Sc}_5 \) |
| \( W_1 \) | \( d_{1,1} \) | \( d_{1,2} \) | \( d_{1,3} \) | \( d_{1,4} \) | \( d_{1,5} \) |
| \( W_2 \) | \( d_{2,1} \) | \( d_{2,2} \) | \( d_{2,3} \) | \( d_{2,4} \) | \( d_{2,5} \) |
| \( W_3 \) | \( d_{3,1} \) | \( d_{3,2} \) | \( d_{3,3} \) | \( d_{3,4} \) | \( d_{3,5} \) |
| \( W_M \) | \( d_{M,1} \) | \( d_{M,2} \) | \( d_{M,3} \) | \( d_{M,4} \) | \( d_{M,5} \) |

Key: \( \mathcal{Sc}_i \)—Sustainability criteria \( i \), \( W_r \)—Weight assigned to \( \mathcal{Sc}_r \), \( D_i \)—Design option \( i \), \( d_{r,i} \)—user assigned utility (scalar value) that measures the performance of \( D_i \) on a given \( \mathcal{Sc}_r \).
sum model. The SI is defined as a crisp value that is an aggregated measure of the performance of an alternative (such as a design option) along various sustainability dimensions (economy, environment, health and safety, resource utilization, project administration, etc.). The underlying assumption here is the additive/commutative utility model. The contextual translation means that the total utility of a given design proposal (as measured by the sustainability index) depends on its individual utilities in the various decomposed elemental sustainability indicators (KPIs). This assumption holds for most extant theories of utility and is particularly true of the concept of “generalised additivity.” Also the use of weighted sum model assumes that the decision criteria can be expressed in the same unit of measure. This is achieved by using dimensionless numerical scores (i.e., scalar quantity) in the sustainability appraisal process.

Let $SI_i$ (for $i=1, 2, 3 \ldots M$) represent the final sustainability index (a crisp value), of design alternative $D_i$ when all the decision criteria $d_{ij}$ are considered. The next problem is how to compute $SI_i$. There are different MCDM methods such as weighted sum model (WSM), weighted product model (WPM), and the analytical hierarchical process (AHP). The references [17–20] contain detailed description of these methods. This paper focuses on the weighted sum model because it is the most widely used MCDM method. It is also considered sufficient for formulating an underpinning mathematical model for quantitative sustainability appraisal. The decision is further buttressed by the fact that a review of some completed case study major projects and the application of MCDM techniques in practice indicates that the weighted sum model is widely used for practical decision making in real life situations. It is therefore considered valid enough to develop a mathematical foundation for sustainability appraisal.

In the context of maximising the sustainability of a design proposal, the preferred design option would be the alternative that gives the highest corresponding value of Sustainability Index (SI). Again to maintain simplicity of the model formulation, the sensitivity of various indicators and their impact to ranking of alternatives is not considered within the scope of this paper. Another underlying assumption in all MCDM methods is that the decision maker can quantify performances for a given design evaluation. Thus, the decision maker is considered to have sufficient knowledge and expertise (including experiential knowledge) in scoring the performance of design alternatives. Computational analysis is performed using these assigned dimensionless scores (scalar quantities). These assumptions generally hold and are widely used in practice for complex project situations. Hence, they are considered to be valid for the mathematical model formulation. Section 4 (see Table 2) discussed the KPIs that define the decision-making criteria $d_{ij}$ in Eq. (1). The next section discusses cognitive/reasoning maps as decision aids to guide in assigning scores to design options.

5.3. Cognitive/reasoning map as decision aid for infrastructure sustainability appraisal

In order to apply the sustainability KPIs in practical situations, it is necessary to understand the relationship and interactions between the various indicators at sub-elemental levels. Reasoning (cognitive) maps play significant roles in problem structuring. This holds for quantitative methods in evaluating sustainability decisions. As part of the problem structuring, this section develops reasoning maps that show the cause and effect relationship between the various indicators. It uses the reasoning map to illustrate the complexities of the interaction between the various indicators. Understanding the interactions would facilitate the sustainability appraisal process. This approach builds on previous applications among researchers to perform multi-criteria dimensional evaluation of decision alternatives [4,7,17]. Fig. 2 shows a snapshot of the proposed cognitive/reasoning map.

The cognitive/reasoning map is interpreted as follows:

- **Waste management**: A waste management process increases the direct (construction) cost of an infrastructure project (+). However, efficient material reuse and/or recycling and the use of prefabricated material improves the waste management processes and reduces the associated cost (−) and cumulatively impact the initial cost.
- **Ecology**: Eco-designs can increase initial cost (+), but such design concepts have long-term positive impact on both the environment and tourism.
- **Constructability**: Poor constructability increases initial construction cost both in terms of delays and associated claims, materials wastage as well as rework (+). However, good constructability has a reverse impact. Early contractor and supplier involvement (ECI/ESI) increases the chance of meeting constructability goals. Procurement techniques such as design and build, and partnering also facilitate ECI/ESI. This results in good value engineering practice, when combined with constructability design audit [15,16].
- **Public access and occupational safety**: Inadequate provision of public access (e.g., through temporal access facilities/routes for construction) can lead to serious problems of coordination and interface man-
agement between subcontractors (e.g., materials delivery subcontractors). In extreme cases, this can lead to unhealthy and unsustainable human relations that could even result in physical fights and injuries at site. Thus, although provision of good site access leads to increase in the initial construction cost (+), it generally improves the occupational safety and health and hence contributes to a sustainable construction environment (Fig. 2).

6. Conclusions and recommendations

This paper discussed the development of indicators, computational methods, and analytical models for sustainability assessment. It reviewed current sustainability research and highlighted the existing problems and gaps. The problems are further compounded by an absence of a systematic approach to sustainability appraisal at micro-levels. The research focused on investigating solutions to the problems engendered by lack of problem structuring. It emphasised that such problem structuring and systematic approaches are required in order to translate strategic sustainability objectives into project-specific concrete actions. The paper discussed the development of KPIs for infrastructure sustainability assessment using the proposed SUSAIP framework.

The paper also discussed the role of cognitive maps as decision aids to facilitate sustainability assessment (Section 5). The map demonstrates that constructability is critical to translate sustainability-driven design solutions into constructed facilities in practice. This is because any sustainable design decisions and/or specifications made in earlier stages could be changed into other unexpected forms at the construction stage due to constructability problems. However, the cognitive map illustrated that both early contractor involvement (ECI) and early supplier involvement (ESI) would minimise constructability-related problems including cost associated with delays, claims, wastage and rework etc. Moreover, some of the indicators are site-specific and project-specific in nature. ECI and ESI give contractors and suppliers the opportunity to give advice and/or specific ideas earlier (example regarding route for dumping materials, noise or waste production of a specific plant) etc. The result of the questionnaire-based indicator validation with stakeholders shows that some indicators are vulnerable to the vagaries and changes in society’s priorities. It raises some intergenerational issues in the context of temporal time-space dimensions of sustainability as a concept.

The developed indicators incorporate the major international sustainability metrics (economy, environment, and society). It also incorporates other performance-based indicators such as health and safety, resource utilization and aspects related to project management all of which can be measured quantitatively during construction. Thus, the proposed SUSAIP framework can be used at various project stages including design, construction, operation...
and maintenance and demolition. The framework would enable designers to formulate strategies to design for sustainability by incorporating these depths of performance criteria. Design considerations would include (i) environmental impacts; (ii) innovative solutions that optimise the use of resources including designing for durability, constructability and deconstruction, (iii) material reuse, recycle and waste management, (iv) impact of design decisions on the wider ecosystem etc. and (v) innovative construction methods and technology. Specific design strategies to address construction technology include (i) reduction in waste generation by using prefabricated materials and (ii) reusing moulds and formwork by using steel moulds. The validated taxonomy of sustainability indicators would enable designers to comprehensively address these issues [13,14]. Moreover, a complementary cognitive map such as the one discussed in Section 5.3 of this paper would further reduce cognitive load on designers so that they focus on other design tasks.

The paper also proposed step-by-step processes and underpinning decision models for sustainability assessment. The mathematical models constitute the foundation for computational analysis in quantitative-based decision making, using a crisp value—the sustainability index. The proposed methodology and analytical models were validated using a mega-infrastructure project as a case study discussed in Part 2 [48]. This validation moves the SUSAIP framework beyond experimental formulations into practical application. The results and case study observations indicate huge potential applications of the model in practice. The methodology and computational models discussed could form a basis for process automation in the broader context of sustainability appraisal and organisational knowledge management [47].

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