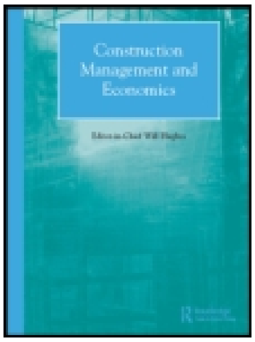

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Sustainable construction management: introduction of the operational context space (OCS)

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Sustainable construction is an emerging field of science that aims at incorporating the general sustainable development concepts into conventional construction practices. While the foundation of knowledge in this field is continuously expanding, sustainable construction is not yet standard industry practice. One major technical barrier that hinders enacting sustainable construction is the absence of an application framework that integrates both sustainability and construction practices at an operational level. This shortcoming is being addressed through a three-dimensional operational context space (OCS) that achieves the sought integration aspect. The three dimensions of OCS are: (1) project life cycle phases; (2) project executing entities; and (3) sustainability performance parameters. Such OCS facilitates the association of responsibility, by assigning each sustainability requirement to a specific project entity (or entities) during specific project phase(s), and further provides a numerical assessment for construction projects using sustainability as a criterion. Steps of constructing the OCS and how it could be employed in the evaluation and benchmarking of a project's environmental performance are examined, along with sample illustrations in the area of construction waste management.

Keywords: Sustainability, sustainable construction, environmental impact, integration, benchmarking.

Introduction

The construction industry has been proved to be a potentially damaging exercise to the surrounding environment, and one that offers considerable opportunity for improvement (Addis and Talbot, 2001; Langston and Ding, 2001). Accordingly, *sustainable construction* has been introduced as:

> a holistic process in which the principles of sustainable development are applied to the comprehensive construction cycle, from the extraction and beneficiation of raw materials, through the planning, design, and construction of buildings and infrastructure, until their possible final deconstruction, and management of the resultant waste (Du Plessis, 2002).

As a discipline, sustainable construction has been evolving since the late 1980s. It continuously gains momentum as increasing evidence about depletion of the environment and environmental loadings becomes obvious. However, regardless of its importance and the expanding foundation of knowledge in the field, sustainable construction is by no means standard industry practice in many world countries (Landman, 1999). Although environmental protective measures, environmental management systems (EMS) and frameworks have become very common at manufacturing and industrial facilities, only a few construction companies have considered the use of a full EMS system in their common practice and projects (Christini *et al.*, 2004).

Several barriers contribute to hindering sustainable construction being the dominant trend of the industry. Principally, these barriers can be summarized into two main categories: general barriers and technical barriers (Matar *et al.*, 2004; Matar, 2007).

General barriers to sustainable construction include:

(1) The lack of expressed interest from different project parties (Du Plessis, 2002). A survey made in the US by the Reed Research Group revealed that almost 60% of industry professionals do not even try to attempt green projects. Only 32% of construction clients have shown interest in pursuing green construction (RRG, 2003).

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(2) The lack of training/education in sustainable design/construction (Du Plessis, 2002).
(3) The slow or very slow recovery of investment in sustainable construction practices (Du Plessis, 2002; RRG, 2003).
(4) The higher initial cost of sustainable building alternatives (Landman, 1999).

Technical barriers to sustainable construction include:

(1) The lack of a well-defined set of sustainable construction practices that can be practically engineered in construction projects (Pearce and Vanegas, 2002b). Although several best practice guidelines exist covering different environmental performance aspects, there is little formally structured information about procedures associated with the inclusion of environmental issues in the construction process (Cole, 2000).
(2) The need for a mature and well-developed framework of application for sustainable practices in construction. While certain efforts have been ongoing to control and enhance individual aspects of the environmental qualities of built facilities, detailed comprehensive approaches that integrate these individual research strands have generally been lacking. Each of the currently available systems has its own set of assumptions and limitations, and is designed for utilization by specific participants in the building process (Scheuer and Keoleian, 2002). This hinders the capacity of different industry stakeholders to cooperate in a uniform and constructive way.
(3) The disagreement about an optimum project delivery structure to attain sustainability. Different approaches to a project delivery structure imply different approaches to integrating sustainability as a rather new concept/ethic within the current practices of the construction industry. Very few studies have considered the effect of project planning on the capacity to adopt sustainability practices (Chen *et al.*, 2005). As sustainability is concerned with the complete life cycle, a building needs to be considered from its design and construction, through the operational stage, to its deconstruction. Project structure is one of the necessities to make meaningful recommendations (Myers, 2005).
(4) The need for effective drivers for change for different parties in the construction industry (Vanegas and Pearce, 2000; Du Plessis, 2002).

Yet, with the importance of sustainable construction being acknowledged, significant research efforts have been made to produce tools that help to assess and eventually mitigate the environmental impacts of buildings and construction activities.

Scientifically speaking, there are two basic methodological frameworks for assessing the environmental impacts of a given object: environmental impact assessment (EIA) and life cycle assessment (LCA). The two approaches share the same aim, but they differ in that in EIA the focus is on assessing the actual environmental impacts of an object located on a given site and in a given context, whereas LCA is formulated to assess the non-site specific potential environmental impacts of a product regardless of where, when or by whom it is used. As objects of environmental performance assessment, buildings strictly fall somewhere in between the strict scopes of EIA and LCA, and most of the currently utilized building assessment methods are in a sense crossbreeds of the two approaches (Crawley and Aho, 1999).

A recent study included a survey carried out on behalf of the US General Services Administration (GSA), which counted more than 150 building performance and sustainability evaluation tools for the purpose of selecting a mostly reliable and comprehensive tool for the US GSA sustainable construction/ procurement needs. At the first screening, only 34 of these tools qualified as sufficiently comprehensive building evaluation tools covering multiple sustainability criteria, adopting a 'whole building' approach and covering more than one life cycle phase. At the second screening stage, only five sustainable building rating systems scored positively on all of the screening criteria. These were the BREEAM, CASBEE, GBTool, Green Globes US and LEED (Fowler and Rauch, 2006).

Overall, these environmental building assessment methods/tools are invaluable tools that assist in the creation of a body of knowledge and expertise within different design teams and the building industry as a whole, and cumulatively facilitate the assimilation of environmental issues into standard industry practice (Cole, 1998). However, many of these tools have limitations that may hamper their effectiveness in making sustainable construction a standard practice of the industry (Ding, 2004). Among these limitations is their limited capacity for associating specific environmental responsibilities with specific project stakeholders, and a tendency to act as post-design evaluation tools rather than providing interactive participation throughout a project life cycle (Cole, 1998; Ding, 2004). Another area of confusion is the pronounced disagreement about the number of performance criteria considered, ranging from six major criteria in case of LEED, 18 criteria in case of BREEAM to almost 170 criteria in case of the C-2000 assessment method (Cole, 1998; Ding 2004; Fowler and Rauch, 2006).

Finally, most of these tools show inflexibility and inadaptability to different project types and regions of the world (Cole, 1998; Ding, 2004).

With an aim to address the major technical barrier of lacking an integration framework that integrates both sustainability and construction practices at an operational level, a three dimensional *operational context space* is introduced. This operational context space serves as a modular integration grid comprising three axes: (1) project life cycle phases; (2) project executing entities; and (3) sustainability performance parameters. The context space building units are a number of operational matrices that are used to: (1) facilitate the association of responsibility by assigning each sustainability performance requirement to a specific entity—or entities—during specific project phase(s); and (2) provide numerical assessment for construction projects using sustainability as a criterion. The paper discusses the process of constructing such an operational context space, referred to hereinafter as OCS.

Concepts for framework development

The development of a framework that integrates sustainability within the standard practice of construction faces inevitable difficulties of reassessing priorities, acquiring new skills, and developing and integrating new information into a well-defined project delivery process (Cole, 1998). There are several fundamental issues and concepts pertaining to the development of the framework, considering the desired objectives of achieving integration and realizing operability.

Sustainability practices vs. construction practices

From a management perspective, sustainability practices and construction practices are significantly different in nature. Construction practices are usually well-defined processes/activities that are systematic to execute, and measurable in order to determine achievement. There are codes, specifications and execution standards for construction practices, which can be put into workable construction plans and execution control mechanisms. This is not exactly the case with sustainability practices. In fact, there is a general lack of understanding of the range and type of environmental issues inherent in the construction process, which makes the manner of their inclusion in construction poorly defined, if not inappropriate (Cole, 2000).

Sustainability practices can be shown to exist at three levels (Pearce and Vanegas, 2002a). At the first level, there are *principles*, which are the most general type of knowledge, and are defined as inoperable statements that together form a global set of objectives to define sustainability. Secondly, there are *heuristics*, which represent a set of operable and qualitative, but often unquantifiable, rules that are derived directly from sustainability principles. Finally, there are *specifications*, which are the most detailed level of knowledge, and must be (1) operable; and (2) quantifiable or measurable. For planning and control purposes, most sustainability practices up to date are not yet fully developed to the specification level (Pearce and Vanegas, 2002a).

These differences in the nature and levels of definition between sustainability practices and construction practices again hinder sustainable construction from being standard industry practice.

Clarification of roles and responsibilities

In addition to the aforementioned differences in nature and levels of definition, whereas construction activities are associated with specific executing entities, during specific project phases, sustainability practices are often general guidelines that are not associated with a project entity in particular. Also, they are not related to specific project phases. It is very common in literature on sustainable construction to find a general sustainability requirement placed on a construction project without clearly specifying a path to achievement or a connection to any project life cycle phase/entity. What usually happens is that different industry stakeholders tend to pass responsibility for introducing and executing sustainability practices to each other (Du Plessis, 2002). Considering energy consumption, for instance, it is common to find sustainability requirements demanding a specific rate of energy consumption per square unit area for a construction project, but without specifying where optimization should apply, or to what project phases, or to which discipline of project components.

The necessity for integration

One concept that is fundamental to the attainment of sustainable construction is *integration*. The construction process is one set of interrelated activities that span from the owner's earliest involvement with pre-project planning responsibilities to the completion of project and start-up. The final product of construction is shaped according to the outcomes of all these activities put together. As stated before, it is common that sustainability requirements are placed with respect to the final product without paying sufficient attention to the production process itself. It is totally logical to assume that introducing sustainability throughout all project phases will result in a more 'sustainable' end product.

Accordingly, it is imperative that a framework for sustainable construction can provide and actively integrate the following:

(1) A typical representation of a construction project life cycle that is both holistic and at a sufficient level of detail to determine the impact that process changes have on final project performance.
(2) A selected set of sustainability practices that are quantifiable with respect to the degree of achievement, and also parametric to construction.
(3) A clear definition of project executing entities to facilitate the association of responsibility with respect to carrying out sustainability practices.

Desired qualities in a sustainable construction framework

An extensive review of previous work and literature on sustainable construction suggests a set of qualities that are desirable in an operational framework for sustainable construction. These include:

(1) Having a structure that can be used at various levels of detail, permitting assessment for single and multiple sustainability parameters and executing entities. It should also permit assessments at single and multiple phases of a project life cycle. These features specifically promote a matrix-based structure.
(2) Having an established scoring system that accepts both qualitative and quantitative data in a similar format and in a simple way that provides the ability to revisit and adjust performance criteria as experience matures with sustainability practices in construction (Cole, 1998).
(3) Having a weighting system is also desirable in order to promote and demote the importance of specific parameters if they prove more important.
(4) Being generic so as to be useful in various types of projects and geographical locations (Scheuer and Keoleian, 2002).

The operational context space (OCS)

Research carried out by the authors specifically addresses the development of such a framework. The research aims to develop an integration framework for sustainability practices in construction. This framework has been concluded after an extensive review of several relevant and comparable studies, especially in the field of constructability (Crowther, 2002). The developed platform is described as an 'operational context space' in the sense that it forms a conceptual space bounded by three axes as shown in Figure 1. The OCS axes are:

(1) project life cycle phases;
(2) project executing entities;
(3) sustainability performance parameters.

In fact, framework development has passed several stages before arriving at its final form; these are:

(1) Identification and understanding of the needs and functional requirements, principally including (a) the need for providing a means of structuring environmental information and best practices for various project types according to both phases of a project life cycle, and entities executing the project; (b) providing the capacity for quantitative performance assessment; and (c) that the framework is developed on a standardization approach and using common standards whenever possible.
(2) Exploring concepts and bases for development and implementation, including similar frameworks and standards in comparable disciplines such as constructability research, environmental impact assessment (EIA) frameworks, and life cycle assessment (LCA) methodologies.
(3) Developing framework schematics and algorithms, including the procedures for platform construction, the development and normalization of metrics, and the scoring system and its use for evaluation.
(4) Framework validation and improvement, specifically through the experience and opinions of experts having different backgrounds in the fields of construction, environmental sciences and project management.

The following sections address the construction of framework axes in detail.

Project life cycle phases

There is more or less agreement on using a life cycle approach when dealing with sustainable construction (Langston and Ding, 2001). Without examining the construction process holistically, it is impossible to determine the impact that process changes can have on the end product or final project performance. Accordingly, the OCS has to build upon a holistic baseline description of the construction process from

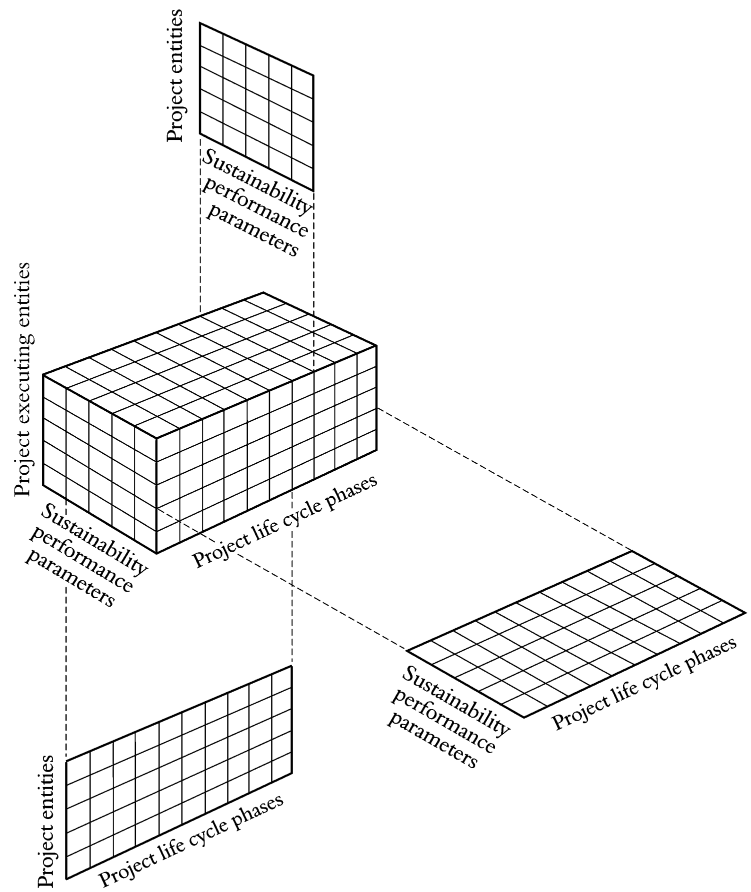

Figure 1 The operational context space (OCS) for sustainable construction

preliminary pre-project planning to at least the start-up phase, if not post-occupation as well.

Although the platform can adopt several project delivery structures, it is based on the engineer/procure/construct (EPC) process, which is favoured for both its integrated and standardized nature. The version used is modified after that prepared by the Construction Industry Institute (CII) in the USA (Back and Moreau, 2000). It provides three different levels of detail. The first level is the EPC macro model dividing the project into major *work packages*. At the macro level, the process is described generically from pre-project planning through start-up. The second level of detail is the micro level, with process units described at the *task* level, where each work package is broken down from the macro model. At this level, the process is described from work package start to work package completion. The third level of detail is a further refinement of the hierarchy and defines specific project *activities* that commonly occur in an EPC project.

The CII EPC model consists of 164 level 3 activities incorporated under 16 key process milestones/tasks and five macro level work packages. The version of the EPC process incorporated in the OCS is modified in some sections to a higher level of detail as necessary to accommodate sustainability practices. Limiting the EPC process detailing to these specific portions is because modelling a process as structurally dynamic and extensive as the EPC process at a very high level of detail could render the model unwieldy. Plus, a higher level of detail would tend to make the process model too specific with respect to project type, company process, or project location. Figure 2 illustrates an overview of the EPC process and the mapping of activities to the OCS.

Project executing entities

A typical construction project can employ executing entities as diverse as architects, various specialist engineers, general contractors, specialist subcontractors and quantity surveyors. Whereas on some projects a single party may undertake the functions of a number of entities, it is still common that there is clear differentiation between such executing entities. This usually creates demand for a management system that

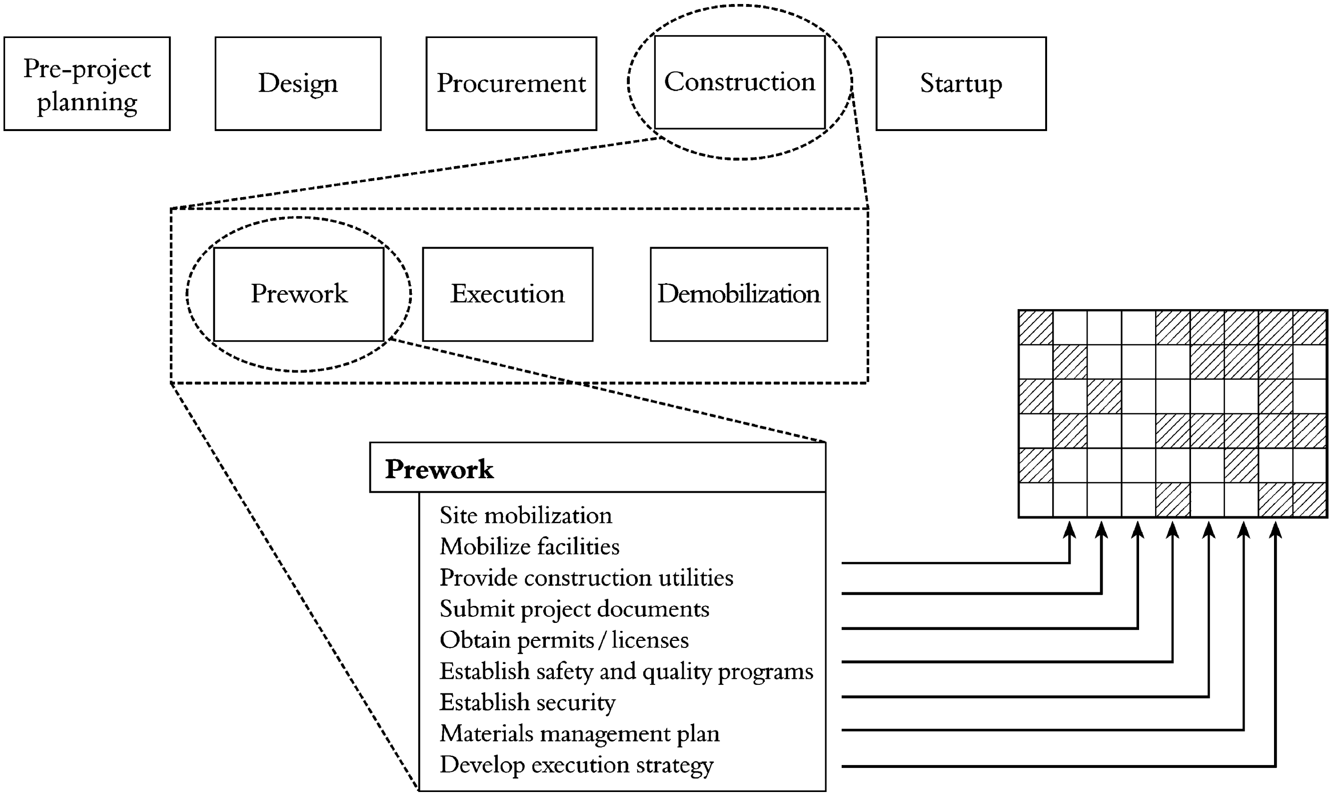

Figure 2 Mapping EPC activities to the OCS

controls the boundaries between different entities and coordinates their output to ensure compatibility with the desired final product.

The matrix-based structure of the OCS permits dealing modularly with any number of executing entities, as each additional entity added is transformed into an additional OCS matrix that holds the attributes of that entity with respect to specific sustainability parameters during specific project life cycle phases.

Sustainability performance parameters

Several governing factors should influence the selection of specific sustainability parameters to be adopted within the platform. Among these factors are the impacts generated by an activity, its boundaries and magnitude, and the specific thresholds of concern—the values, for an environmental impact or resource use, which, if exceeded, cause that impact or use to assume new importance (Canter, 1996). In addition to these, there is the identification of the environmental inventory that is desired to be preserved/protected.

In its broad definition, the *environmental inventory* is defined as a complete description of the environment as it exists in an area where a particular proposed action is being considered. This inventory is compiled from a checklist of descriptors for the physical-chemical, biological, cultural and socioeconomic environments.

Theoretically, an analysis of the environmental inventory should be done for each individual project according to the location of the project and its expected interaction with the environment. However, in the general case, most construction projects comprise a set of standard common activities and procedures, and impact on a defined set of environmental components of a universal environmental inventory (Canter, 1996; Ding, 2004).

As mentioned before, there is a wide variation with regard to the number of environmental performance criteria—and hence the *parameters*—to be included. A range between 6 and 170 has been documented (Cole, 1998; Ding 2004; Fowler and Rauch, 2006). Based on an extensive review of literature on sustainable development, in general, and sustainable construction, in particular, in addition to expert opinion, the authors identified/utilized a set of 18 major sustainability performance parameters, as depicted in Figure 3. The identification was based on a consensus on the significance of these specific parameters in the literature reviewed, which exceeded 100 publications. A sample of these publications includes Venables *et al.* (1994), Canter (1996), Hill and Bowen (1997), Crawley and

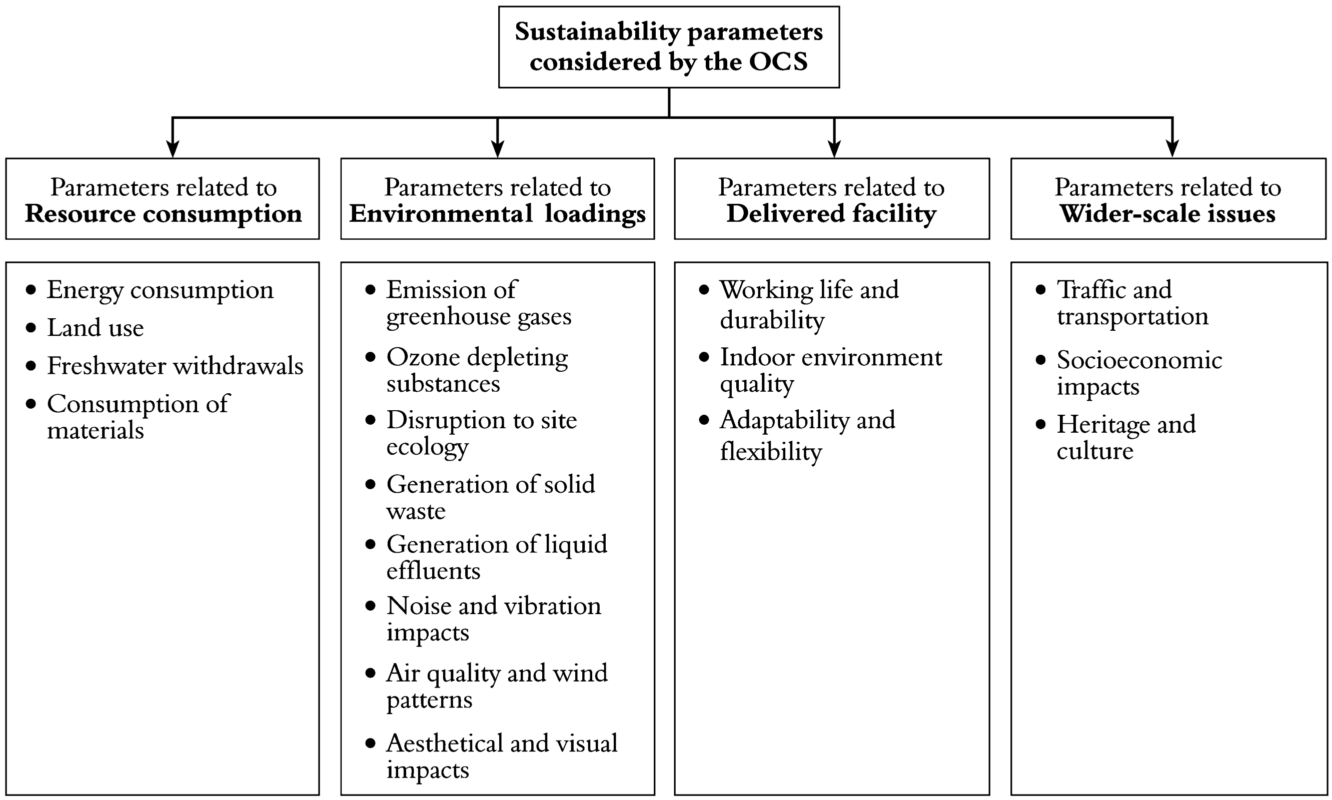

Figure 3 Sustainability performance parameters considered in the OCS

Aho (1999), Cole (2000), Hendrickson and Horvath (2000), Langston and Ding (2001), Roaf (2001), Cole and Larsson (2002), Du Plessis (2002), Pearce and Vanegas (2002a), Pearce and Vanegas (2002b), Outrequin and Charlot-Valdieu (2003), Ding (2004), Shen *et al.* (2005), Wahlström and Brohus (2005), Bunz *et al.* (2006), among many others.

Again, the main selection approach was to choose sustainability parameters that have general agreement over their criteria, and therefore confidence, as to their significance (Cole, 1998).

It is worth mentioning that at early stages of framework development, only 13 sustainability parameters were utilized (Matar *et al.*, 2004). During framework validation, the identified parameters were examined by several experts having different backgrounds: construction practitioners, environmental scientists, ISO 14000 assessors, project managers, and designers with considerable awareness of sustainable construction. As several experts recommended the addition of five extra parameters, the set of parameters implemented within the framework added up to the 18 parameters mentioned. However, for practical purposes, the modular nature of the platform permits adding and/or omitting parameters according to different project cases.

OCS operating structure

Conceptual evaluation planes

At its core concept, the OCS platform incorporates a number of matrices that are subsets of three conceptual planes. These are:

(1) the 'parameter-entity' plane, which comprises a number of matrices at specific project life cycle phases;
(2) the 'parameter-phase' plane, which comprises a number of matrices for each project executing entity;
(3) the 'phase-entity' plane, which comprises a number of matrices for each sustainability parameter.

Examples of these types of matrices are shown in Figure 4. The illustrated matrices display a simplified version of the matrices for:

- overall environmental impacts by different executing entities for the 'construction' phase;
- overall environmental impacts during different project phases for the entity 'general contractor';

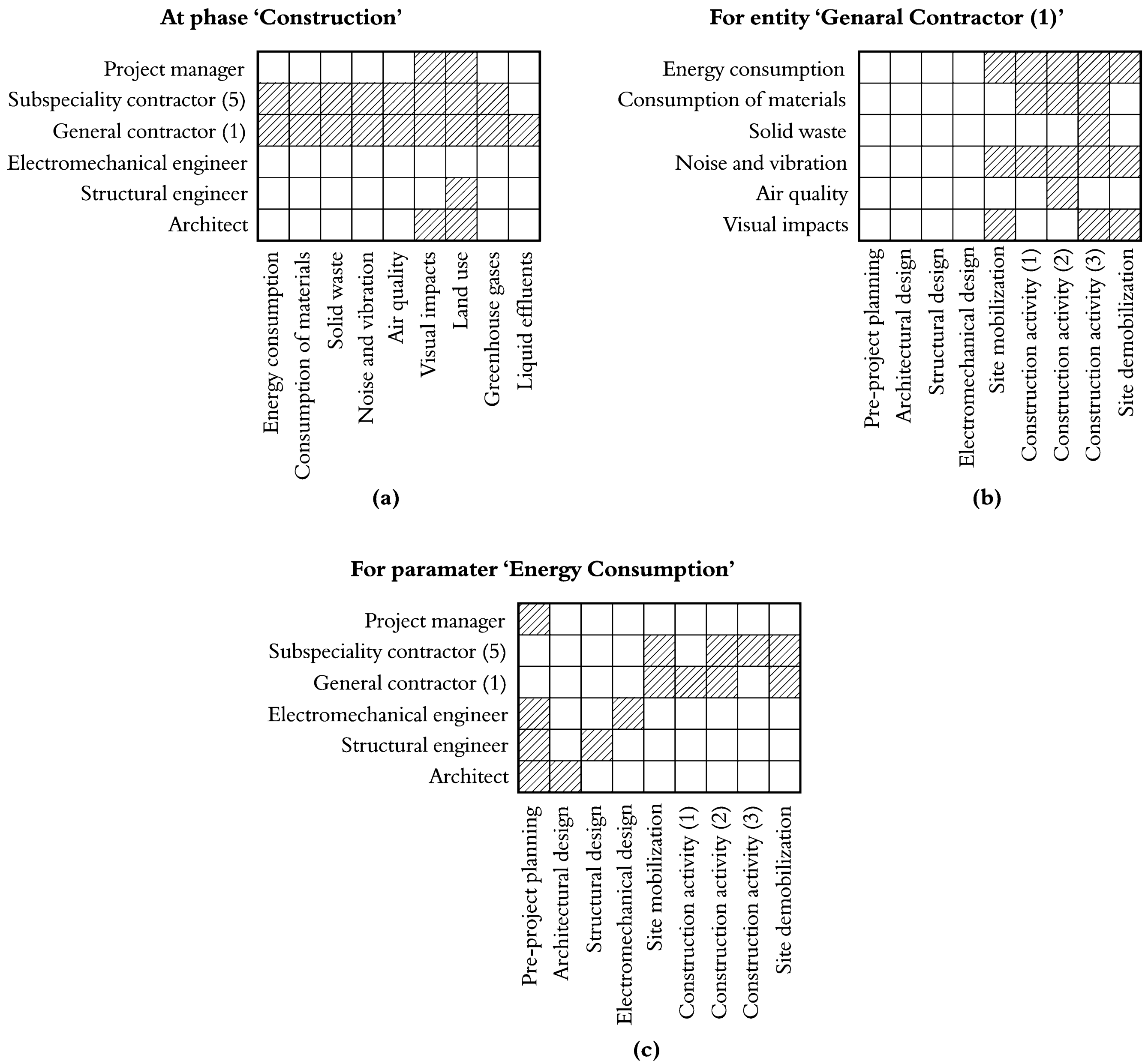

Figure 4 Typical OCS matrices

- overall impact generated by different executing entities during different phases with respect to the sustainability parameter 'energy consumption'.

For each of the three cases in Figure 4, the shaded cells represent environmental performance-dependent values that are calculated with the aid of a predetermined set of evaluation criteria, as elaborated on in the following section.

Metrics and measurement

It is common for construction projects to be evaluated on the bases of simple monetary criteria and/or technical performance. The complexities of sustainability, however, demand different evaluation approaches. Sustainability as a criterion in itself builds on an intricate interaction between several tangible and intangible factors like economic value, technical feasibility, environmental depletion, environmental loadings, social welfare, etc. (Matar *et al.*, 2004). Therefore, at any cell of the introduced OCS, several key criteria for evaluation could/should be combined together to indicate the perceived levels of achievement of sustainable construction objectives at this specific cell. This level of sustainability achievement will be called *sustainability index* hereinafter.

Generally, the OCS platform adopts two approaches to develop metrics and measurements for evaluation purposes of the sustainability indices. These are: (1) physical metrics; and (2) process metrics.

Physical metrics

The 18 sustainability parameters that were previously promoted are each associated with some possible physical metrics. The term 'physical' implies that there are *tangible* measurements for such parameters. Examples include: the energy consumption per square unit area, the percent of waste generated for a specific material, the durability-based net present value (NPV) for a facility, and so forth. Table 1 shows sample physical metrics that could be utilized in the model, and their correlation with the identified sustainability parameters.

Process metrics

The second approach adopted to develop sustainability indices is using process metrics. Most sustainability performance requirements exist in the form of guidelines that would result in making a project more sustainable when followed (Pearce and Vanegas, 2002a). For any given practice, scores could be assigned to signify the level of achievement of these different guidelines as they relate to specific sustainability parameter(s) during specific project phase(s) and by specific project entity (or entities). Appropriately adding up these scores would reflect the environmental performance of any sustainability parameter, project phase, and/or a project entity in focus.

Previous attempts have been made to develop scales for such guideline scores, particularly as they associate with the various sustainability parameters. One approach was to assign a weighted score for each guideline according to expert opinions such that the total score adds up to a specific certain value—100, for instance. Given an existing case/project, a score out of 100 implies its environmental performance with respect to the studied sustainability aspect (TJCOG, 2001). Another approach was to rank sustainability performance on a numerical scale, e.g. −3 to +3 (Outrequin and Charlot-Valdieu, 2003). A third alternative was to use values relative to a qualitative/linguistic scale such as 'poor, average, good and excellent', which can be translated into a numerical scale of '0, 1, 2, 3' respectively. In fact, the use of linguistic/qualitative evaluation is very common in the construction industry (Ding, 2004). This makes that last type of ordinal scaling especially desirable. This type of scale has been

Table 1 Typical physical metrics for OCS sustainability parameters

Parameter	Metric description	Mathematical form
Energy consumption	[Building] total energy use	$\frac{kWh_{delivered}}{month}$ $\frac{cost}{month}$ $\frac{Btu}{month}$
	Source energy	$\frac{kWh_{source}}{month}$ $\frac{kg_{CO_2}}{kWh_{source}}$
	Peak electricity demand	kW
Land use	Land use ratio	$\frac{\text{Gross ground floor footprint m}^2}{\text{Undeveloped site area m}^2}$
Freshwater withdrawals	• Total building potable water use • Indoor potable water • Outdoor water use • Storm sewer	$\frac{m^3}{month}$ $\frac{cost}{month}$
Consumption of materials	Material use ratio	$\frac{\text{tons (material type)}}{\text{Gross building floor area (m}^2)}$
Generation of solid waste	• Waste generation rate • Overall material waste ratio • Hazardous waste	$\frac{m^3}{month}$ $\frac{tons}{month}$ $\frac{cost}{month}$ $\frac{tons\|_{generated}}{tons\|_{inventory}}$ $\frac{\text{weight/volume of waste generated}}{\text{weight/volume of purchased material}}$
Generation of liquid effluents	Quantities of effluents produced	$\frac{m^3}{month}$
Noise generation	• Day–night limits • Noise impact indices • Noise exposure limits	dBA
Air quality	Pollutant daily emission	ppm weight/m^3
Working life and durability	Building maintenance rate	$\frac{hours}{year}$ $\frac{cost}{year}$
Indoor environment quality	• Occupant turnover rate • Absenteeism	$\frac{turnover}{year}$ $\frac{absentees}{occupant \cdot year}$
Traffic and transportation	• Regular commute • Additional traffic generation	mpg $\frac{miles}{week}$

subject to considerable development by Rensis Likert. The Likert scale is most commonly used in marketing and social research, where this type of linguistic evaluation is very common. This scale can have a point range of three, four and up to nine points (Zikmund and Babin, 2007).

The OCS platform specifically incorporates a variation of the Likert scale with a four-point format. Counting was intentionally started from zero to help pronounce cases where no sustainability achievement could be realized. The OCS scale is illustrated in Table 2.

Constructing and utilizing the OCS for environmental performance evaluation

Principally, the OCS intends to serve as an assessment and evaluation tool for sustainability performance of construction projects, as well as benchmarking among them. For these assessment and benchmarking purposes, the platform has to refer to a specific evaluation baseline. By definition, a benchmark or baseline is a test case that serves as a basis for evaluation or comparison. In the case of sustainability and sustainable construction, however, such baseline test case is somehow debatable. As a still developing discipline, sustainability performance boundaries vary between different world regions and countries, and are liable to varying degrees of misinterpretation, bias and inconsistency. While the development of the OCS platform and its operating structure are core tasks in this research, the favouring and promotion of a specific test case are beyond the scope of this work.

The approach adopted for the OCS platform is to develop its own test case—a *reference* space, termed OCS_R, against which the performance of different projects is benchmarked. This reference space builds on the current foundation of knowledge in sustainable construction to depict the 'optimum sustainability performance'. OCS_R is generated at the initial phase of framework commissioning. It is then validated and kept from all future changes except for major revisions to the platform. For every construction project undergoing evaluation, a project-specific version of the OCS matrices should be prepared with actual project performance scores. This project-specific version is termed the *project* space, OCS_P. Such OCS_P would then be benchmarked against the baseline version, i.e. OCS_R.

The following sections explain in detail the construction of both the reference space and the project space, and their usage for evaluation purposes. It is worth noting that emphasis is given to sustainability measurement for the phase-entity planes of the OCS, unless otherwise noted. However, the same concepts presented hereinafter could also be applied to other conceptual planes, i.e. the parameter-phase planes and the parameter-entity planes.

Table 2 The ranking system incorporated in the OCS platform

Scale	Description
0	Poor performance or no achievement at all
1	Average or moderate performance
2	Good practice/performance
3	Best practice/performance

Developing the OCS matrices

Developing the OCS matrices involves four basic steps: (1) data and knowledge acquisition; (2) analysis; (3) normalization of metrics; and (4) constructing the reference and project OCS matrices.

Data and knowledge acquisition

An extensive process of data and knowledge acquisition should be carried out to consolidate all details pertaining to the physical and process metrics of the various sustainability parameters. Efforts directed to attain sustainability best practice guidelines, in particular, will contribute to developing comprehensive process metrics for the sustainability parameters being studied. During this data and knowledge acquisition phase, information is acquired through:

(1) codes, regulations, and environmental standards implemented by different industries—even other than construction;
(2) EIA studies performed for construction projects locally and abroad;
(3) available guides for recommended and best practices of sustainable construction up to date;
(4) interviews with experts and focus group discussions;
(5) process reviews performed to identify possible hazards to the environment, and possible mitigation procedures;
(6) local and overseas experience with similar activities and projects;
(7) analysis of post-project completion reports and audits.

Analysis

Thorough analysis of collected data and knowledge is required to associate metrics, guidelines and process

Table 3 Sample PEAT for the solid waste minimization parameter

Guideline	Phase					Entity				Matrix cell location
	1 PPP	2 D	3 P	4 C	5 SU	1 O	2 MM	3 D	4 C	
Implement separation/segregation/sorting techniques to the waste stream				■					■	(4,4)
Design specifications and detailing should be based on standard sizes of modular materials to help in optimizing material use		■						■		(2,3)
Order materials with different lengths in order to meet different site conditions and requirements			■						■	(3,4)
Designate specific waste storage and dumping areas on site				■					■	(4,4)
Waste storage areas should be labelled by large signage that describes the purpose of the area				■					■	(4,4)
Coordinate material delivery schedule to reduce site storage time			■	■			■			(3,2), (4,2)
Centralize workshop operations on site at specific designated locations				■					■	(4,4)
Screws and fasteners should be used instead of nails and adhesives to ease disassembling of materials if needed		■		■				■	■	(2,3), (4,4)
Cement bags should be covered with plastic to be protected from moisture to avoid deterioration of cement				■					■	(4,4)
Work out the most efficient plan for electrical wires, communications cables, piping and ducts		■						■		(2,3)
Reuse excavated soil for landscaping and noise control purposes				■					■	(4,4)
Increase the use of prefabricated items and units as much as possible		■						■		(2,3)
Establish incentive payments for different material usage and adopting waste management plans	■					■				(1,1)
Reuse concrete and cement wastes in non-structural works				■					■	(4,4)

data to relevant project phases and entities. A set of association tables is generated for each sustainability parameter to facilitate methodical association with regard to phases and entities. These are termed Phase and Entity Association Tables (PEATs). Table 3 represents a sample PEAT prepared for the solid waste minimization parameter.

Normalization of metrics

Following the acquisition and analysis steps, it is necessary to normalize all metrics data collected using the ranking scale adopted in the OCS platform. The performance boundaries for each guideline or physical metric have to be identified and converted to a performance index related to the OCS ranking scale. Tables 4 and 5 exemplify this normalization process for the physical metric 'Percentage of solid waste generated for material *X*' and the guideline 'Reuse concrete and cement wastes in non-structural works'.

Table 4 Normalization of physical metrics

Performance boundary	Evaluation	Ranking
>12%	Poor	0
8%–12%	Average	1
5%–8%	Good	2
<4%	Best practice	3

The performance boundaries selected are arbitrary boundaries for illustration purposes only.

Constructing the reference and project OCS matrices

The PEATs, along with the normalized metrics, are employed to generate the OCS matrices for all 18 parameters. To illustrate such process, consider again the 'solid waste management' example parameter illustrated in Table 3. As shown, each of the listed guidelines is associated with one or more entity or entities during one or more phase(s). The last column

Table 5 Normalization of guidelines

Performance boundary	Evaluation	Ranking
Almost all of the remaining/waste concrete quantity is disposed of/unused	Poor	0
30–50% of the remaining concrete quantity/waste is reused for non-structural purposes	Average	1
50–70% of the remaining concrete quantity/waste is reused for non-structural purposes	Good	2
More than 70% of the remaining concrete quantity/waste is reused for non-structural purposes	Best practice	3

allocates each guideline to a specific matrix cell according to the association process. Only representative phases and entities are used in the example. However, in the actual complete model, a guideline is analysed with respect to the whole set of 164 activities present in the CII EPC process and can be associated to entities at a level of detail and definition as desired.

After the association to matrix cells, the matrix cells with guidelines shall hold a numerical value representing the degree of achievement with respect to the associated guideline(s). When constructing the reference benchmark matrix, the degree of achievement is assumed to be 100%, hence a value of 3.0 is added for each guideline allocated to the cell. In the case of an actual project, however, a value reflecting the actual degree of achievement for the project at hand should be used. Figure 5 illustrates the development of the reference benchmark matrix based on Table 3.

Considering cell (4,4), for instance, eight guidelines have been allocated to the cell. Accordingly, at top performance, it holds a value of 24.0. The sum of each row represents the contribution of each entity in achieving good practice with respect to a specific sustainability parameter—here, the solid waste minimization. The total of row sums represents the global benchmark value for the parameter at hand.

Constructing the OCS

For each of the 18 sustainability parameters, the matrix development process illustrated in the previous section is carried out: physical metrics are obtained and normalized. Guidelines used to reflect process metrics are collected, analysed and associated to phases and entities in PEAT tables. In the case of the reference space, however, the values filled in any matrix are all set to the maximum possible score, being 3.0, as indicated in Table 2. This is because the reference space OCS_R should necessarily reflect the optimum sustainability performance. OCS_R cell values can be multiples of 3.0 in case of cells harbouring more than one guideline.

For a project undergoing assessment, the process of constructing the OCS_P simply reduces to calculating actual performance values according to actual project performance with respect to the same guidelines adopted in the reference space OCS_R. The resultant matrices together constitute the project space OCS_P for that specific project.

Environmental performance evaluation using the OCS

The OCS adopts equations and calculation techniques after the weighted factor scoring model described by Meredith and Mantel (2000). For either the reference or project space (OCS_R/OCS_P), the magnitude of each matrix is calculated using a simple algebraic sum equation. For any parameter matrix (M_p), the magnitude of the matrix is:

$$\sum_i \sum_j M_{i,j} \tag{1}$$

where i is the number of rows depicting the project entities, while j is the number of columns depicting EPC activities.

This equation might be taken one step further by introducing *weights.* Up to this point, it has been assumed that all of the sustainability parameters incorporated have equal importance. This assumption was made because the relative importance of sustainability performance parameters with respect to each other is, again, an area of much debate. Cole (1998) states that:

> weighting remains the most theoretically complex area to address within the development of building assessment methods and is dependent of a much greater understanding of the environmental impacts of building. The weighting of environmental criteria is relevant at a number of scales—global, local and a project-by-project basis and there is no consensus on the factors which should appropriately be used in deriving applicable values.

The case is the same for sustainability performance guidelines, except in very clear cases. However, should future research prove this to be incorrect, or even if an OCS user decides to emphasize the relative importance of any specific parameter(s)/guideline(s), the magnitude of a parameter matrix should be calculated as:

$$w_P * \sum_i \sum_j w_{i,j} * M_{i,j} \tag{2}$$

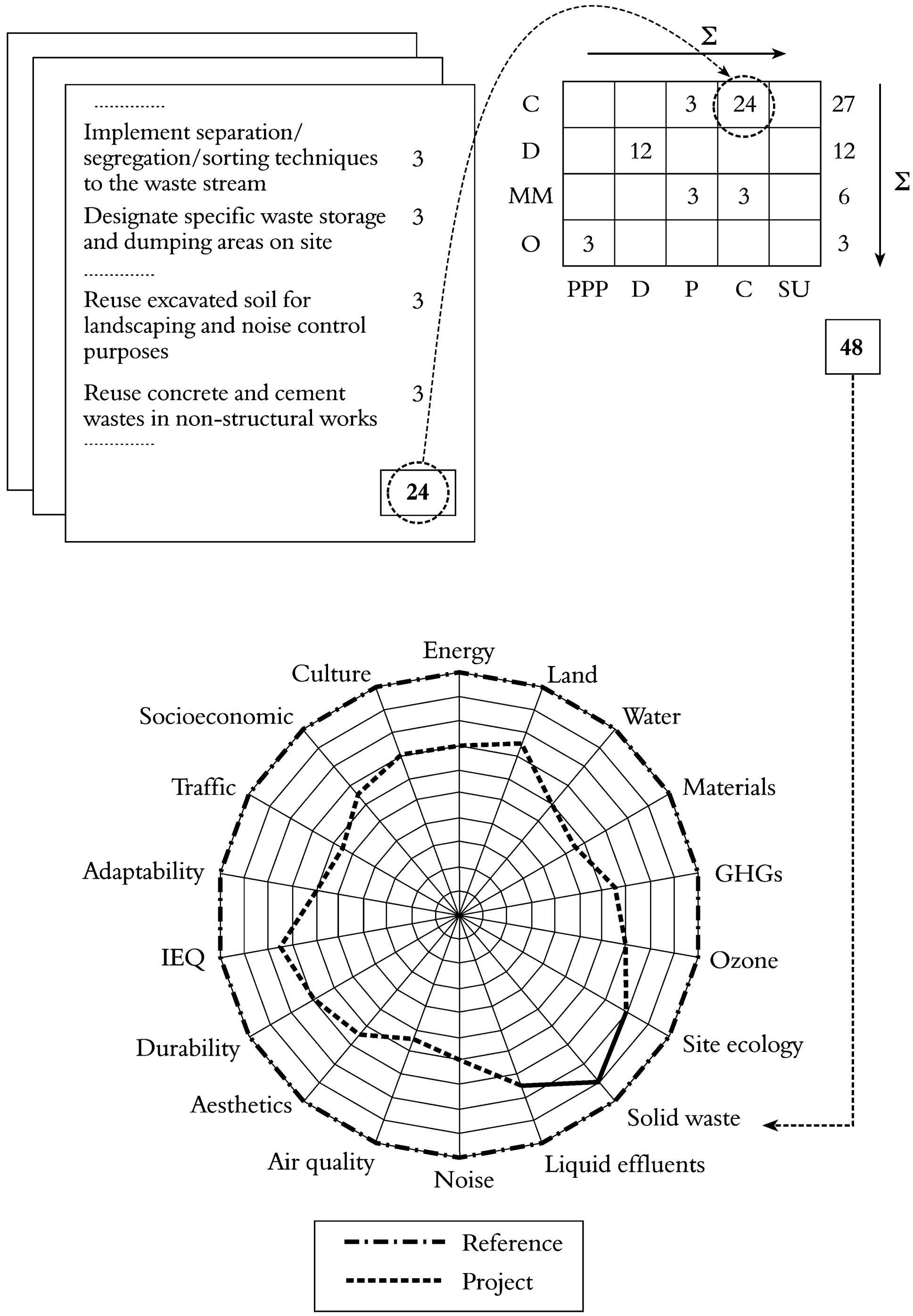

Figure 5 Development of reference and project values (with graphical illustration of performance evaluation)

where w_P is an external weighting value for parameters among each other, while $w_{i,j}$ is an internal weighting value for the guidelines related to a specific parameter.

The completion of this process will result in two sets of values representing the *reference* and the *project* spaces. Each set holds 18 values corresponding to the 18 sustainability parameters incorporated in the model.

At this point, benchmarking can be carried at two levels:

(1) At the plane level to depict project performance with regard to a specific sustainability parameter:

$$\frac{M_P|_{\text{project}}}{M_P|_{\text{reference}}} \leq 1.00 \tag{3}$$

(2) At the overall space level to depict the overall project sustainability performance. In this case, an aggregate sum of project scores for all sustainability performance parameters is compared to the corresponding aggregate sum of the reference space matrices:

$$\frac{\sum_{P=1}^{18} M_P\big|_{\text{project}}}{\sum_{P=1}^{18} M_P\Big|_{\text{reference}}} \leq 1.00 \tag{4}$$

Typically, a radar graph may be plotted to illustrate the performance range of any project under assessment, as illustrated in Figure 5.

Conclusions and future work

An integration platform has been introduced for sustainable construction, namely the operational context space (OCS). The context space comprises a number of operational matrices that are used to (1) facilitate the association of responsibility by assigning each sustainability parameter performance requirement to a specific entity (or entities) during specific project phase(s); and (2) provide numerical assessment for construction projects using sustainability as a criterion. The modular nature of the model permits an infinite number of variations in order to suit virtually any type of construction project and situation. It can be even adapted to serve industries other than construction. Further publications planned by the authors will address a number of application-oriented aspects of the OCS.

Owing to the nature of the topic and its novelty, however, much remains for future work. Sustainability indices have to be developed and refined for different sustainability parameters. Much of the future work by experts—from both fields of construction and environmental sciences—should be directed to identifying the relative weights of sustainability parameters and the dynamics between parameters. The issues of selecting an optimum project delivery structure to attain sustainability and the optimum scaling system for informative sustainability assessment still need extensive investigation. An automated version of the OCS should further facilitate widespread implementation and enhance the framework usage.

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