A SERVICE-ORIENTED FRAMEWORK FOR SUSTAINABILITY APPRAISAL AND KNOWLEDGE MANAGEMENT

SUBMITTED: February 2005
REVISED: March 2005
ACCEPTED: September 2005 at http://www.itcon.org/2005/17/
EDITOR: C. Anumba

O O Ugwu, Assistant Professor
University of Hong Kong, Hong Kong
email: oougwu@hkucc.hku.hk

SUMMARY: *This paper proposes a service-oriented framework and architecture for integrated sustainability knowledge management in construction. The proposed architecture is based on a survey conducted amongst industry professionals in Hong Kong SAR. The objective was to identify problem areas in infrastructure design and construction management practice as they currently militate against sustainability appraisal for innovative infrastructure delivery. The identified stress-points were then used to formalise user requirements for (ICT-based) decision support to achieve sustainable design and construction in the AEC sector. A clear understanding of the end-user requirements would facilitate translation into system functional specifications and enhance systems development efforts. The survey indicates that robust frameworks and architectures are required to address the multidimensional user requirements. These include frameworks that provide services and processes for integrated data exchange, information access, intelligent document and knowledge management. The paper discusses the findings from this survey, the framework and evolving architecture to address the identified user requirements. Recommendations are given to address these pedagogical dimensions of sustainability in construction.*

KEYWORDS: *infrastructure sustainability, service-based decision support, knowledge mapping, integrated knowledge management, learning-oriented organisation, multi-criteria decision model*

1. INTRODUCTION & BACKGROUND TO STUDY

Sustainable development as a concept has been gaining increasing popularity across various sectors including the construction industry since the Brundtland Commission Report in 1987 [WCED, 1987]. 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* [UNCED, 1992], and was followed by the South African summit in 2002 [UN, 2002]. In response to the international summits, several countries set up strategies to meet their sustainability objectives at the macro level. For instance the government of Hong Kong Special Administrative Region (HKSAR) set up a Sustainability Development Unit (SDU) responsible for mapping the National Sustainability Goals and Objectives [HKSAR, 2003]. Current efforts have focused on developing tools for environmental assessment of buildings (e.g. using the HK-BEAM in Hong Kong). However, significant gaps exist in construction research addressing integrated sustainability appraisal as part of innovative infrastructure design and delivery.

In order to achieve the broad goals of sustainability it is necessary to adopt a holistic approach that considers the impacts of various types of civil infrastructure such as roads, bridges, water projects etc on the environment, economy, and social aspects of a society– “the triple bottom line”. There is therefore need for generic tools that provide decision support for sustainability appraisal of different types of projects. Moreover, in the specific context of achieving sustainable construction, the real determinant of the success of any national goal remains the translation of strategic policy initiatives to concrete design guidelines and actions at the micro level. Such translations at the knowledge level [Newel, 1982] are required to enable designers to assess the impacts of their design decisions as they contribute to achieving (or militate against) the National sustainability goals. To achieve this micro-level objective requires top down and bottom up approaches in analysing and synthesising current practices in designing for sustainability [Bierkeland, 2002] and how construction organisations harness, deploy and manage sustainability knowledge. The need to address sustainability assessment at the project level has been discussed and highlighted in literature [Odysseus, 2003], [Ugwu et al, 2003], [Ugwu, 2003], [Zhou & Lowe, 2003]. Other researchers have also highlighted the potential roles of information management systems and ICT in achieving the objectives of sustainability [Chen & Zhou, 2003]. In addition some researchers identified and expounded the need to understand, harness and manage intangible corporate assets in the broader context of organisational knowledge management [Nonaka & Toyama,2002], [Nonaka et al, 2000], [Snowden, 2002], [Khalfan et al, 2002], [Ugwu et al, 2005a]. The research reported in this paper is investigating the knowledge processes associated with designing and constructing for sustainability at the project level. The main research issue is the need to entrench a learning-oriented culture in construction by deploying robust frameworks (including computational/decision models and ICT) as decision aids and tools to support construction knowledge workers. This would be achieved in the form of services required to support different processes associated with sustainability design and construction appraisal. These services could be deployed as compossable IT functionality services across distributed organisations, underpinned by other complementary technologies such as web-services and eXtensible Markup Languages (XML) including the evolving e-business XML (ebXML) standards.

The rest of the paper is organised as follows. The next section outlines the research questions and highlights the significant contributions of the work. Next, the paper describes the research methodology and discusses results of the questionnaire survey used to identify problem areas in current approach to sustainability appraisal and knowledge management in infrastructure projects delivery. The paper then uses the findings from the survey and the identified problem areas to propose a service oriented framework that addresses the various existing problems and issues identified. It then describes the case study project used in the research investigation and a prototype implementation of the service-oriented framework and architecture. Finally the paper draws some conclusions and gives recommendations for future work.

2. RESEARCH QUESTIONS & SIGNIFICANCE

The main research question addressed is: what is the current state of sustainability appraisal and knowledge management in infrastructure projects delivery? This is divided into several related questions; (i) what are the problem areas that militate against sustainability design and construction in practice, (ii) what is the appropriate decision-making model and (iii) what framework and knowledge representation techniques would be suitable to capture the resulting decision model and computational and knowledge management requirements for improved sustainability appraisal through process automation. The requirement is for framework(s) that extends the multi-faceted epistemological and ontological dimensions of knowledge (i.e. tacit, explicit, embedded, organisational, knowledge conversion and sharing etc) and acts as a precursor to entrenching good sustainability knowledge management processes in construction organisations. These requirements in sustainability underpinned the research model/framework. It is also the significant contribution of the research discussed in this paper. The next section discusses the research methodology.

3. METHODOLOGY – QUESTIONNAIRE DESIGN AND SURVEY

The research methodology involved a combination of questionnaire surveys, follow-up interviews with industry professionals some of whom participated in the survey, and project-based case study. The case study was conducted over more than two years using a mega-infrastructure project that spanned the design and construction stages of the project. This provided an in-depth analysis and understanding of the critical issues involved in sustainable design practice including appraisal and knowledge management at organisational level (focusing on knowledge capture, re-use and retention during construction). The study also identified various stakeholders involved in infrastructure delivery processes within the construction supply chain, their specific roles and requirements in the context of sustainable design and construction. Section 4.1 describes the actors and their roles in sustainable construction projects delivery, while section 4.4.1 describes the case study project in detail.

3.1 Questionnaire design

The questionnaire had five sections designed to elicit different information. These included: basic demographic data of respondents, industry's awareness and understanding of sustainability as a concept, how sustainability is addressed in the construction industry, mechanisms for learning and disseminating sustainability knowledge at organisational levels, and a provision for a respondent to comment on the subject. In order to identify the problem areas in sustainability practice at micro-project levels for subsequent use in user requirements analysis, each section included targeted detailed structured questions such as eliciting a respondent's awareness of sustainability appraisal including procedures, tools, and techniques.

3.2 Survey Sample

The survey sample was industry professionals taking a post-graduate degree course [MSc (Eng) in Infrastructure Management]. 30 questionnaires were distributed, and 26 were returned giving a response rate of 80.6% (4 respondents did not consider themselves as having sufficient industrial experience to complete the questionnaire). The 26 respondents work in 21 different construction organisations. The distribution of respondents by type of organisation includes; 18 from 13 different consulting firms, 4 from contractor organisations, and 4 from client organisations. Further analysis of respondents' demographic data revealed that all the major construction organisations in Hong Kong had at least one respondent. Some of these organisations have strong international operations. The positions of respondents include: project manager, deputy project manager, project engineer, assistant resident engineers, environmental consultant, assistant engineer, and engineers. 11 of the 26 respondents also expressed interest in receiving a report on the survey findings, and willingness to further share their experience on infrastructure delivery and management within the context of sustainability through follow-up interviews in the research. This sample of industry practitioners studying a part-time postgraduate course was particularly good because the respondents represented a good cross-section of potential/typical end-users (i.e. designers, site engineers and project managers etc). The ensuing section discusses the findings from the survey analysis.

3.3 Survey Results: User requirements for decision-support in infrastructure sustainability appraisal

3.3.1 Awareness of sustainability initiatives and instruments (tools)

Fig. 1 shows the level of awareness of different sustainability tools and initiatives.

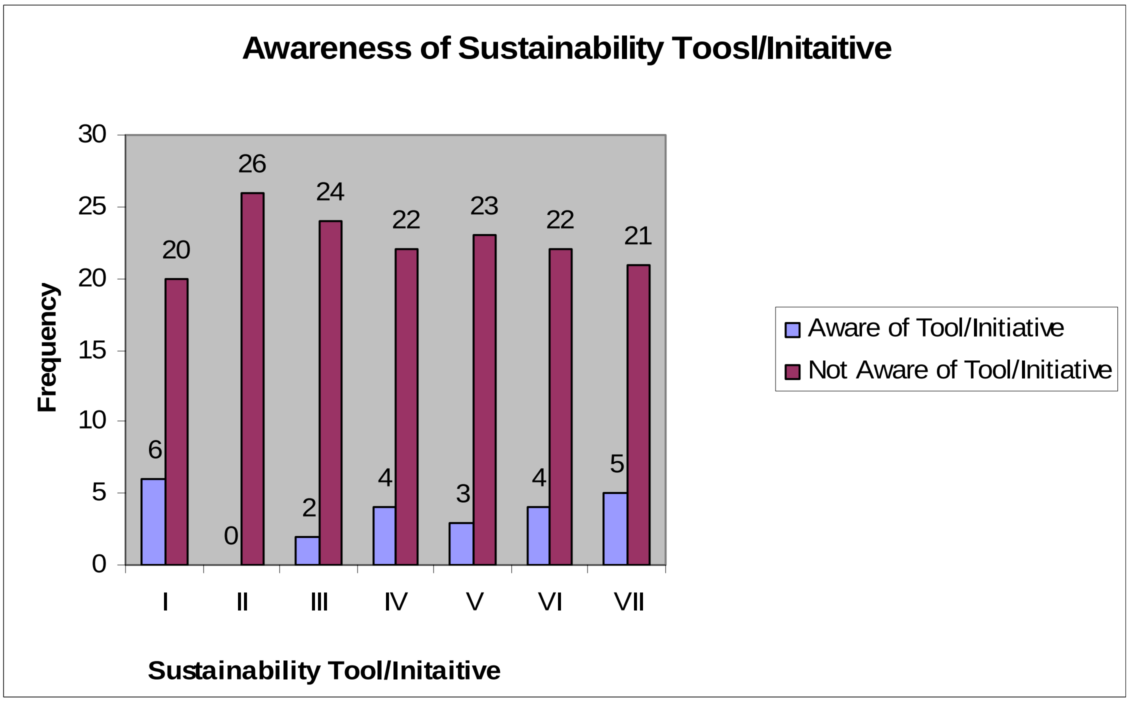


FIG. 1: Awareness of Sustainability Assessment Tools & Initiatives (Source: analysis of survey data)

Legend:
I = SUSDEV21 - Sustainable Development 21, by the HKSAR Planning Department, [HKSAR, 2003] [Hong Kong Government, 2004]
II = GRI - Global Reporting Initiatives, (convened by the Coalition for Environmentally Responsible Economies (CERES) in partnership with the United Nations Environmental Program (UNEP) in 1997. Started operating as an independent organisation in 2002 [GRI, 2005])
III = BREEAM – Building Research Establishment Environmental Assessment Method, (developed by the Building Research Establishment (BRE) United Kingdom) [BREEAM, 2004])
IV = SPeAR – Sustainability Project Appraisal Routine, (developed in-house by Ove Arup and Partners)

V = UNCSD – United Nations Commission on Sustainable Development
VI = LEED – Green Building Rating System, (developed in the United States of America) [US Green Building Council, 2004])
VII = HK-BEAM – Hong Kong Building Environmental Assessment Method, (HKSAR tool established in 1996 based on UK's BREAM) [CERT, 1999]

3. 3.2: Aggregate issues that impinge on sustainability design practice

Fig. 2 shows a summary of issues that respondents perceive as impinging on sustainable design and construction in practice.

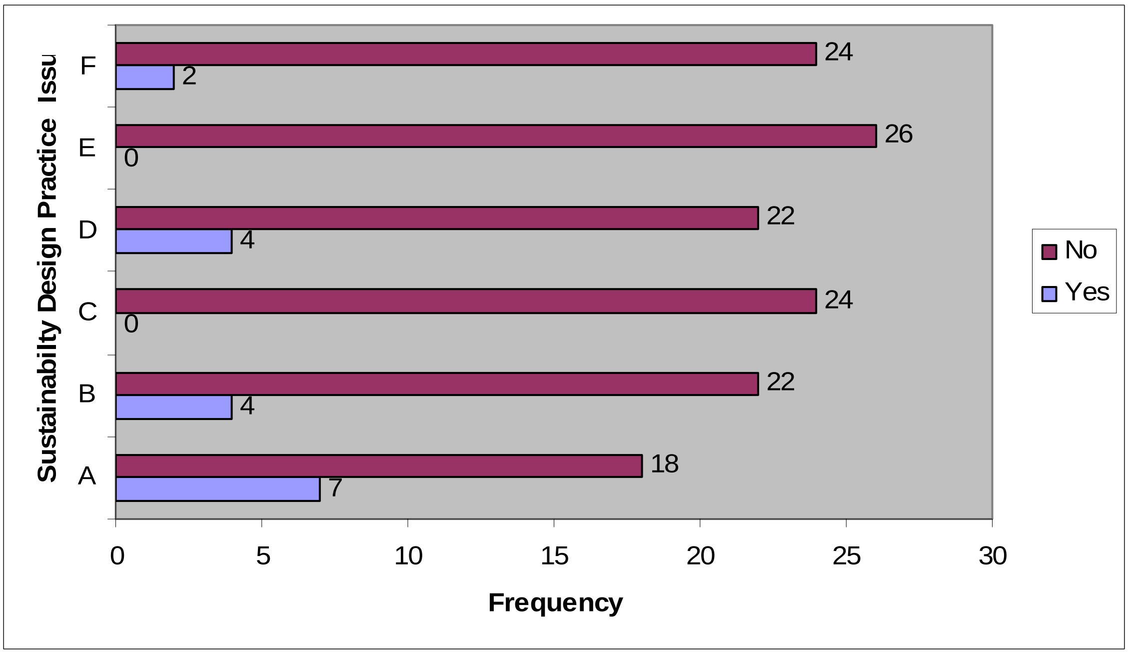


FIG.2: Aggregate issues related to sustainability practice at project level (Source: Analysis of survey data)

Legend:
A = Incentives exist to design for sustainability in infrastructure projects, **B** = Organisation has guideline/manual/standard on sustainability decision-making, **C** = Organisation has a department or personnel responsible for sustainability, **D** = Organisation has defined procedures to address sustainability of infrastructure projects, **E** = Use tools to evaluate the sustainability of infrastructure projects, F = Respondent involved in sustainability-driven project

Fig. 2 indicates that the critical issues to address include establishing personnel responsible for sustainability issues in infrastructure projects, developing frameworks for sustainability assessment and tools for quantitative analysis to support multi-criteria decision making (MCDM). Other issues to address include assigning construction knowledge workers to sustainability-driven projects for hands-on experience, and developing procedures and guidelines to design and construct for sustainability. The respondents also outlined their current organisational knowledge sources for infrastructure sustainability. The sources and associated frequencies include ISO9000 (2 respondents), ISO14001 (1 respondent) and SPeAR (2 respondents from the same organisation).

3.3.3 Learning and dissemination mechanisms for sustainability knowledge management

Table 1 gives a summary of various approaches to knowledge dissemination at organisational levels. Fig. 3 shows a graphical display of the mean scores. Section 3.5 gives detailed description of the survey results.

TABLE 1: Sustainability Learning & Knowledge Dissemination Mechanisms (Source: Analysis of survey data)

Knowledge Sources/Sharing & Dissemination Mechanisms	**Current Level of Implementation in Organisation**						**Potential Contribution to Sustainability Knowledge**					
	Not at all (%)	Some Extent (%)	Moderate Extent (%)	Large Extent (%)	Very Large Extent (%)	N	Not at all (%)	Some Extent (%)	Moderate Extent (%)	Large Extent (%)	Very Large Extent (%)	N (%)
External training programs and seminars on sustainable construction	5 (23.8)	11 (52.4)	2 (9.6)	2 (9.6)	1(4.8)	21	2(10.5)	2(10.5)	7(36.8)	7(36.8)	1(5.3)	19
Self learning of individuals	7 (33.3)	7(33.3)	4(19.0)	1(4.8)	2(9.5)	21	1(5.6)	4(22.2)	7(38.9)	5(27.8)	1(5.6)	18
In-house guidelines and procedures on design and construction for sustainability	7(33.3)	7(33.3)	6(28.5)	1(4.8)	0(0.0)	21	1(5.3)	1(5.3)	9(47.4)	6(31.6)	2(10.6)	19
Mentoring schemes (working with senior colleagues experienced in the subject area)	8(38.1)	5(23.8)	8(38.1)	0(0.0)	0(0.0)	21	0(0)	2(10.5)	8(42.2)	7(36.8)	2(10.5)	19
On-line delivery of resources on sustainable construction (e.g. guidelines, procedures, checklists etc)	7(35.0)	7(35.0)	5(25.0)	1(5.0)	0(0.0)	20	2(10.0)	2(10.0)	8(40.0)	6(30.0)	2(10.0)	20
Provision of IT tools for automated sustainability assessment of design alternatives	10 (47.4)	7(33.3)	4(19.0)	0(0.0)	0(0.0)	21	1(5.3)	5(26.3)	6)(31.6)	6(31.6)	1(5.3)	19
Post-project review to capture lessons learned on sustainable design and construction	11 (52.4)	7(33.3)	1(4.8)	2(9.6)	0(0.0)	21	1(5.0)	0(0.0)	9(45.0)	7(35.0)	3(15.0)	20
In-house seminars (e.g. using case studies on sustainability-driven projects)	7(35.0)	8(40.0)	4(8.0)	1(5.0)	0(0.0)	20	0(0.0)	2(10.6)	7(36.8)	5(26.3)	5(26.3)	19

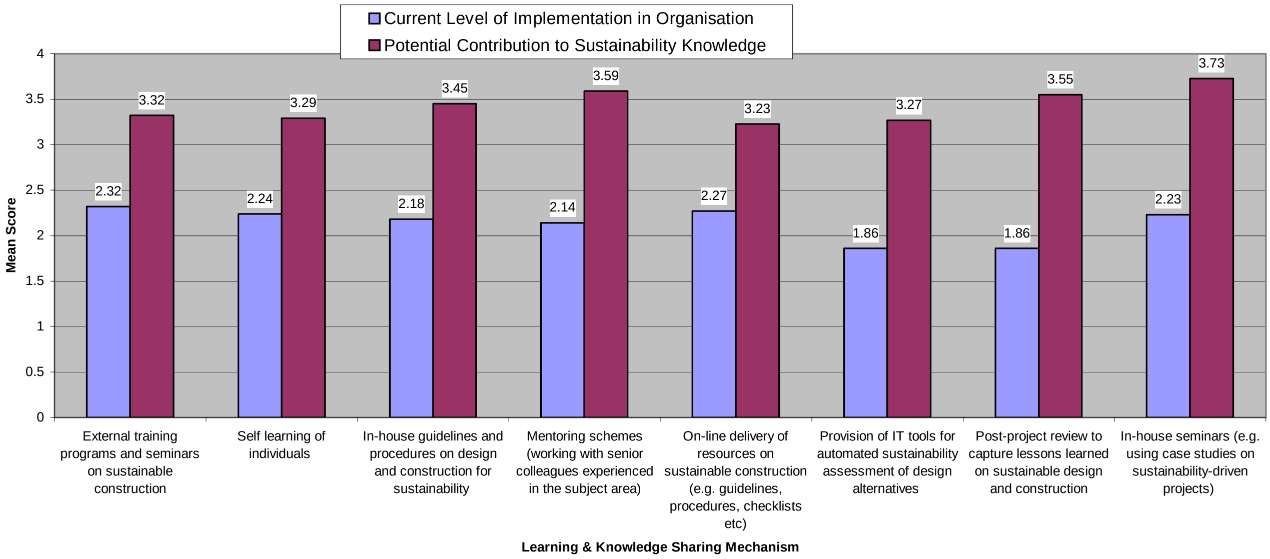


FIG. 3: Sustainability KM dimensions - learning & dissemination of sustainability knowledge (Source: Analysis of Survey Data)

Key: Mean score on the y-axis (5-point likert scale): 1 = Not at all, 2 = Some Extent, 3 =, Moderate Extent, 4 = Large Extent, 5 = Very Large Extent

3.4 Benchmark Index for sustainability knowledge dissemination mechanisms

Using the survey responses, the benchmark index for sustainability knowledge management mechanism was computed, by transforming all the numerical scores for the various knowledge dissemination constructs, to numerical indices in order to assess their relative rankings. The benchmark was calculated using the following formula:

$$SK_{bi} = \frac{\sum w}{AN}, (0 \leq SK_{bi} \leq 1) \quad (1)$$

where,

w = weighting given to each factor by the respondent, which ranged from 1 to 5, where 1 is "not at all" and 5 is "a very large extent".

A = the highest weighting, which is 5, and

N = the total number of respondents

Table 2 shows the computed benchmark indices. In order to have a better appreciation of the differences between the perceived current level of implementation and corresponding potential contribution to sustainability knowledge, the ratios of the two were computed using the respective benchmark indices in Table 2. Fig. 4 shows the graphical result.

TABLE 2: Summary of Benchmark Index

Knowledge Source/Sharing Mechanism	Current Implementation		Potential Contribution to Knowledge	
	Weighted Index	Rank	Weighted Index	Rank
In-house seminars (e.g. using case studies on sustainability-driven projects)	0.39	6	0.74	1
Post-project review to capture lessons learned on sustainable design and construction	0.34	7	0.71	2
Mentoring schemes (working with senior colleagues experienced in the subject area)	0.40	4	0.69	3
In-house guidelines and procedures on design and construction for sustainability	0.41	3	0.67	4
On-line delivery of resources on sustainable construction (e.g. guidelines, procedures, checklists etc)	0.40	4	0.64	5
External training programs and seminars on sustainable construction	0.44	2	0.63	6
Self learning of individuals	0.45	1	0.61	7
Provision of IT tools for automated sustainability assessment of design alternatives	0.34	7	0.61	7

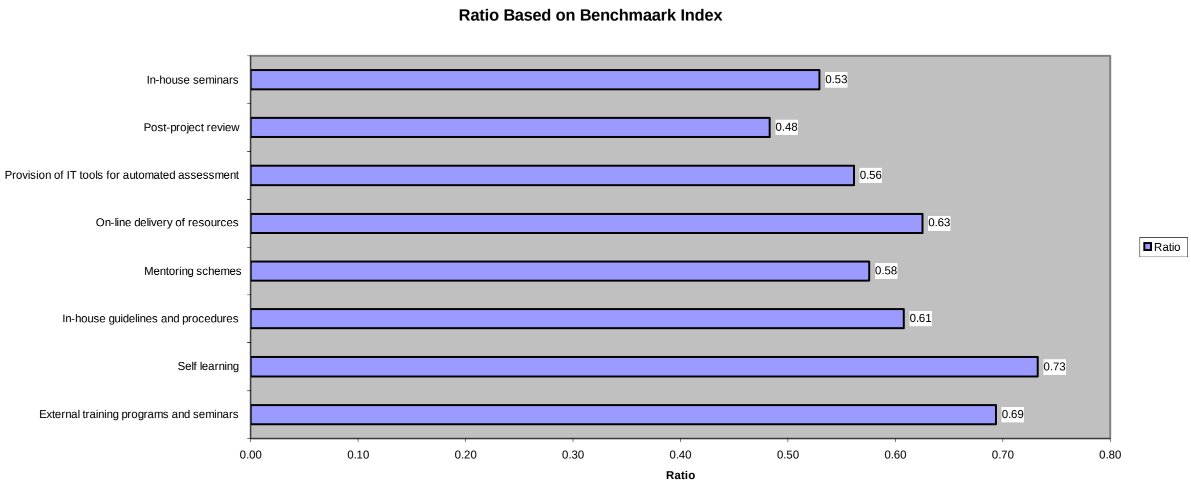


FIG. 4: Graph of ratio of level of implementation/potential contribution to sustainability knowledge based on benchmark index (Source: Analysis of survey data)

3.5 DISCUSSION OF SURVEY RESULTS

The survey results suggest that there is not much difference in the mean scores of the level of implementation for the various knowledge sources and sharing/dissemination mechanisms. Table 2 shows that the highest weighted index is 0.45 for self-learning, and the lowest is 0.34 for provision of IT tools for decision support. However, there is a noticeable difference between the mean scores for the current levels of implementation and potential contributions to sustainability knowledge, in all cases (Fig. 4). Also Table 2 shows that the weighted index for potential contribution to knowledge has a maximum value of 0.74 for in-house seminars and a minimum value of 0.61 for both self-learning and provision of IT tools. Whilst self-learning is generally seen as an effective mechanism in normal educational process, it may not be so effective in the problem domain. This is because there is limited understanding and documented cases of construction projects and infrastructure sustainability, to facilitate any self-learning process. Also the effectiveness of any IT –based decision support will be dependent on the level of functionalities (services) available to users. In theory the nominal minimum score for acceptance (which is 2 on the likert scale) is 0.40 as computed using the weighted index formula. Using 0.40 as a benchmark, then it is observed that values for IT implementation and Post project review are very low, while

Provision of IT tools for automated sustainability assessment of design alternatives with a value of 0.34 (Table 2) is actually below the minimum threshold value of 0.40 for acceptance.

Fig. 4 shows the ratio (current level of implementation / potential contribution to knowledge) for various knowledge dissemination mechanisms. These ratios indicate considerable scope to improve current sustainability knowledge management and dissemination. The scores in increasing order are for post-project reviews (0.48), in-house seminars (0.53), provision of IT tools for automated assessment (0.56), mentoring schemes (0.58), online delivery of resources (0.63), in-house guidelines (0.65) and external training programs and services (0.69). Only self-learning with 0.73 has a ratio above 0.70 which could be considered acceptable. This clearly indicates that organisations need to do more in the other 7 key knowledge dissemination mechanisms.

The above ratios together with the weightings given to the potential contributions of the various knowledge sources and sharing/disseminating mechanisms to sustainability knowledge indicate a requirement for appraisal techniques as well as robust content/context-specific document and knowledge management strategy and framework for the problem domain. These indicate a requirement for content-driven knowledge management solutions, underpinned by a robust ICT framework. This result and the conclusions were distributed to 11 of the respondents who had indicated their willingness to participate. One respondent commented as follows (edited to maintain anonymity of the respondent):

> "(The) research result and the conclusions are correct. Most (construction organisations do) not have formal (infrastructure) to collect data/experience from previous project in order to improve the quality of project works, (and they rely on) the experience of their project manager or director. (However), if these employees are terminated or resign, all the data (and knowledge) will be lost when they leave the company…"

The survey results (TABLES 1 & 2) provide some insight on the areas researchers and construction organisations need to investigate further for effective learning and dissemination of sustainability knowledge as well as other forms of construction knowledge. These results form the basis for investigating the framework discussed in the ensuing sections.

4. A SERVICE-ORIENTED FRAMEWORK

This section uses the findings from the survey to give a critique of current state of sustainability knowledge management in construction. It combines the findings from the survey as well as the follow-up interviews and observations from the detailed project-based sustainability case study, to outline potential solutions. Advances in information and communications technology (ICT), underpin such solutions. Possible ICT implementation solutions include; (i) developing XML-based schemas to facilitate seamless data exchange/document management and content retrieval by end users, and also between different applications; (ii) using Role-Based Access Control (RBAC) Model to control service availability to users over distributed networks [Armour, 2003]; and (iii) Web-based architecture for distributed collaboration and problem solving. These solutions are discussed in Table 3.

TABLE 3: Knowledge Sharing Mechanisms: Framework for Sustainability Appraisal & Knowledge Management in Construction

Knowledge Sharing Mechanisms	**(Description of current solution) /Limitations of existing solutions**	**Potential service-based and/or ICT-driven solution**
External training programs and seminars on sustainable construction	(Face to face seminars, illustrated using appropriate case studies etc,) but there exist very few documented case studies, exacerbated by inadequate knowledge capture of lessons learnt.	Video conferencing [Nahar et al, 2001]
Self learning of individuals	(On line based and formal learning), Problems include lack of real time digital capture images at construction stages for intuitive web-based self-learning. .	Web-based eLearning, Multimodal interfaces that enable users to switch from one mode to the other. Use smart tools and techniques such as intelligent agents etc [Anumba et al, 2005], [Ugwu et al, 1999]
In-house guidelines	(Context-driven and project-specific). Knowledge	Electronic document management systems (EDMS),

and procedures on design and construction for sustainability	management systems, not yet fully deployed and available support tools are mostly tailored to document storage and retrieval systems. Still predominantly passive mode of learning, and not active/intuitive enough.	and intelligent information retrieval (IR) using Role-Based Access Control (RBAC) paradigm. Workflow-based solutions for business process automation, underpinned by organisational, and enterprise knowledge models [Armour, 2003].
Mentoring schemes (working with senior colleagues experienced in the subject area)	(Mentors' knowledge capture predominantly achieved through face-to-face interactions). Lack of digitisation for storage and re-use at appropriate organisational interfaces. Need to harness organisations intellectual/knowledge assets often engrained in peoples and processes, map these into organisational digital nervous system through an evolutionary process. Essential to address in a distributed problem-solving context since these experts can be quite few, and geographically dispersed.	Ontology-driven using various techniques as appropriate including agent-based KM & learning, multimodal interfaces that enable users to switch to different forms/mode of interaction, Augmented reality etc [Uschold & Gründinger, 1996],[Butz et al, 1999]
On-line delivery of resources on sustainable construction (e.g. guidelines, procedures, checklists etc)	(Online search solutions). Current problems include information overload in part due to existing unintelligent search modes/tools/engines/paradigms. Pretty static and not dynamic/adaptable. Not active. Predominant unstructured data, information or knowledge on sustainability design etc. Thus current state often results in end-users drowning in information, but lacking in knowledge. Solutions need to be complemented with intelligent search tools to provide other bits like guidelines procedures, etc	Robust content management. Intelligent search engines and web-based document retrieval and delivery. Can be facilitated using agent-based information retrieval, and the evolving web services paradigm, including context-sensitive search engines. Underlying this is a view of *intelligent agents as carriers and distributors of knowledge at the service level* [Uschold & Gründinger, 1996],[Butz et al, 1999] [Kerschberg et al, 2004], [Anumba et al, 2005].
Provision of IT tools for automated sustainability assessment of design alternatives	Lack of adequate understanding of cognitive-intense processes associated with integrated decision support and knowledge management in the context of sustainability assessment in infrastructure projects delivery. Need to integrate multi-criteria decision-making models (both quantitative and qualitative) to cater for various dimensions (i.e. taxonomy) of sustainability assessment (such as economy, social, environment, resource utilisation etc) that capture domain complexities.	Collaborative distributed problem-solving paradigms using techniques such as web-based systems, augmented reality, distributed artificial intelligence (DAI) techniques [Ugwu et al, 1999]. Underpinning **services** could be delivered using appropriate architectures, Multi-Agent Systems (MAS), Object-based knowledge capture (data, processes and computational methods). Object-based solutions could deliver computational analysis tools (multi-criteria analysis models, methods, hybrid approaches and techniques that encapsulate quantitative mathematical models and fuzzy-based algorithms such as credit-based scoring and scaled-scoring systems. Computational techniques, algorithms and tools, delivered as system level services to end-users [Butz, et al, 1999], [Saaty, 1977], [Saaty, 1980].
Post-project review to capture lessons learned on sustainable design and construction	Project teams are often disbanded at end of project and some are oftentimes re-assigned at critical project phases before end of the project. Employees often leave organisations with their experiential knowledge (a situation also exacerbated in the era of downsizing and outsourcing). Knowledge of construction process often lost due to inadequate capture of knowledge processes and lack of enabling strategies/systems at micro operational levels.	Frameworks for ontology-driven service-oriented knowledge management and decision support (including agents and multi-agent systems support) in sustainability knowledge management. ICT tools for knowledge capture at micro project levels (detailed design and construction stages etc) – focus here need to address strategies for data, information and knowledge capture, and persistence storage mechanisms and tools [Kerschberg et al, 2004], [Morikawa & Kerschberg, 2004].

4.1 Description of actors and roles in an integrated environment for sustainable design & construction

The identified actors and their expected roles in designing and constructing for sustainability in a virtual integrated sustainable construction environment/practice include:

- *Design engineer*: Generates different design options, inputs different design configuration (that includes sustainability related parameters), needs to generate sustainability assessment reports, requires tools that provide means to evaluate and compare different design options
- *Site engineer:* Site-level supervision, retrieves previously generated reports, evaluates the implications of design change on sustainability, needs tools to facilitate evaluation of design configurations to generate an update report, capture lessons learnt including context-specific critical incidents and problem resolution during construction, compose and upload documents that encapsulate knowledge of associated procedures & process information. Uploaded documents need to be persistently stored for distributed organisational use
- *Other employees (e.g. inexperienced user):* Need to access guidelines and procedures on sustainability appraisal/assessment, input different design configuration (according to guidelines, e.g. questions asked, hints, or keywords, etc), and obtain sustainability assessment reports.
- *Suppliers:* Provide information on material performance specifications, in the context of sustainability, inputs data/information into database for persistence storage, may also need to update materials database as appropriate.

The next section discusses the architecture for construction enterprise-level integration, to provide various services required by the identified actors to perform their functions and professional roles in an integrated environment.

4.2. Service-Oriented Architecture and Framework for Sustainability Appraisal & Knowledge Management

This section discusses a service-oriented architecture to address the user requirements details identified from the workflow analysis conducted using case study project (a sustainability-driven infrastructure described in section 4.4.1). Fig. 5a shows the conceptual multi-layer architecture designed to facilitate distributed sustainability knowledge management, and implement the framework described in Table 3.

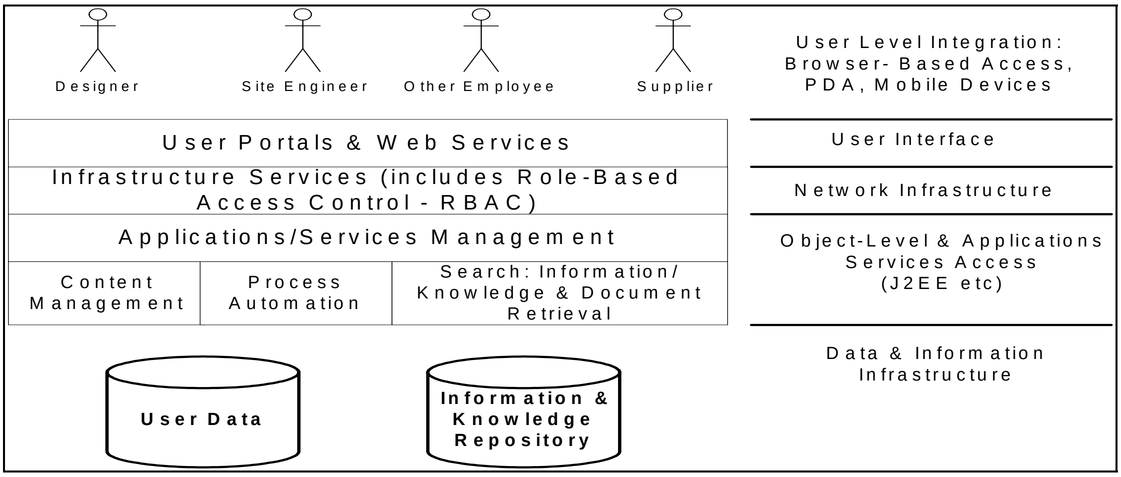


FIG. 5a: Sustainability Learning & Knowledge Dissemination – A Service Oriented Architecture for Construction Enterprise Integration

The case study workflow analysis examined different functional roles, tasks, data, and information needs at the micro level. Other issues examined include existing organisational approaches to disseminating design and construction related data and information, as well as knowledge capture and sharing at operational (i.e. project) levels. This required an appraisal of existing project management systems and the inbuilt functionalities, focusing on issues such as critical incidents capture to underpin future organisational learning. The resulting framework is high-level and implementation-independent, giving the flexibility to adopt appropriate design solutions at the system implementation level. It focuses on enterprise-level integration for sustainability knowledge management. FIGURE 5b captures the clusters of services that are required at user and system application levels, for the implementation.

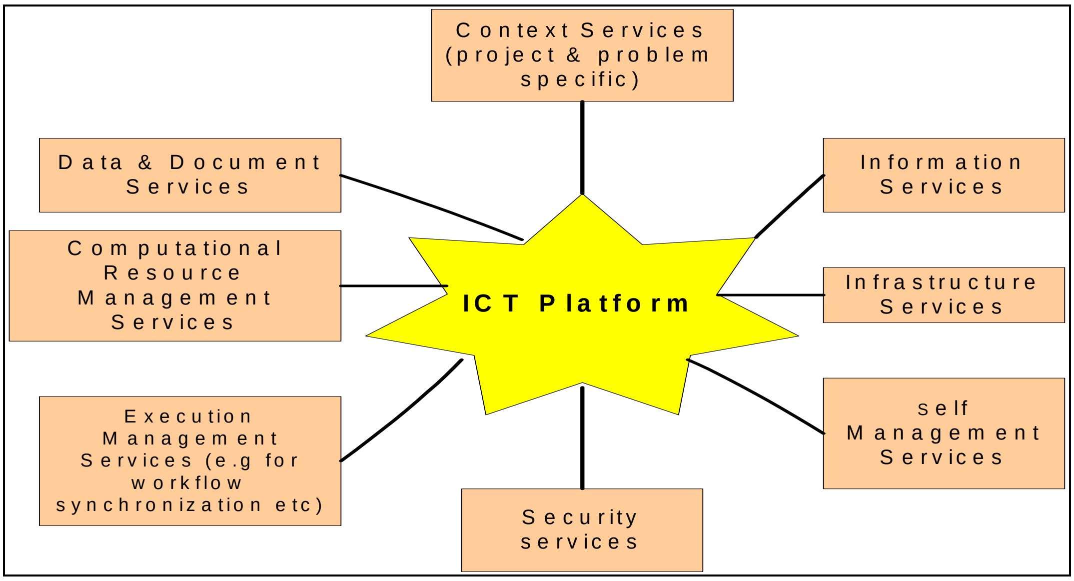


FIG. 5b: System level services for Integrating Knowledge Production & Supply in Construction Supply Chain (adapted from [Ugwu et al, 2005a])

Table 4 summarises different services to facilitate integrated decision support and knowledge management.

TABLE 4: ICT- based Decision Support for Sustainability Appraisal and Knowledge management

Architectural Layer/Tier	**E-Services & Description**
Data & Information	• Information Services: At the heart of information services is a requirement for mechanisms to facilitate a user's ability to access, compose and send required information, and at the appropriate format. The requirement here is for robust user interface design to ensure that; (i) the user has the flexibility to view data/information which need to be customised so that only relevant information are delivered to appropriate designated user and guard against information overload (e.g. by deploying of context-sensitive help and search facilities), (ii) the underlying supporting operations like persistent data storage (e.g. using database management systems etc) and data marshalling and transformation techniques, need not be visible to the user.
Object-level & applications service	• Context Services: Mechanisms are required to enable users to exchange domain problem and context-specific knowledge (e.g. through facilities like web-based discussion forums and web-based document management). It also includes context-sensitive searches and online help provisioning. • Self-Management Services: In the case of shared resources, in an integrated construction supply chain network, this refers to mechanism and management protocols that are used to negotiate access and resources use over the network
Network infrastructure	• Infrastructure Services: This refers to mechanisms for controlling resources (including computational resources) over the network. It addresses issues such as prioritisation in shared resource allocation. • Resource Management Services: Mechanisms are required for starting computational resources (e.g. programs and applications) and for controlling and monitoring the execution of such resources. Role-Based Access Control (RBAC) techniques could be deployed to control user-assigned resources over a network. The focus here is on access to computational resources, data, and information as necessary (see section 4.3 for details). • Security Services: This refers to mechanisms to ensure that information is protected as a valuable asset to an enterprise.

User-level integration (browser PDA, Mobile devices) & User interface	• Data & Document Management Services: This relates to mechanisms required for putting in files and documents, and also retrieving stored files, data, information and documents. It includes mechanisms for document management and version control. It requires standard user interface services including smart and intelligent user interfaces

The next section illustrates initial prototype implementation of the service-oriented framework, focussing on data, information management and sustainability appraisal services.

4.3 Examples of Service Level Implementation – KnowMSAIP Prototype

The proposed framework has been implemented in a pilot web-based prototype, to identify the limitations and any enhancements required in the conceptualized model. Table 5 summarises some of the system services.

TABLE 5: System-level Services for Knowledge management and Decision Support in Sustainability Appraisal

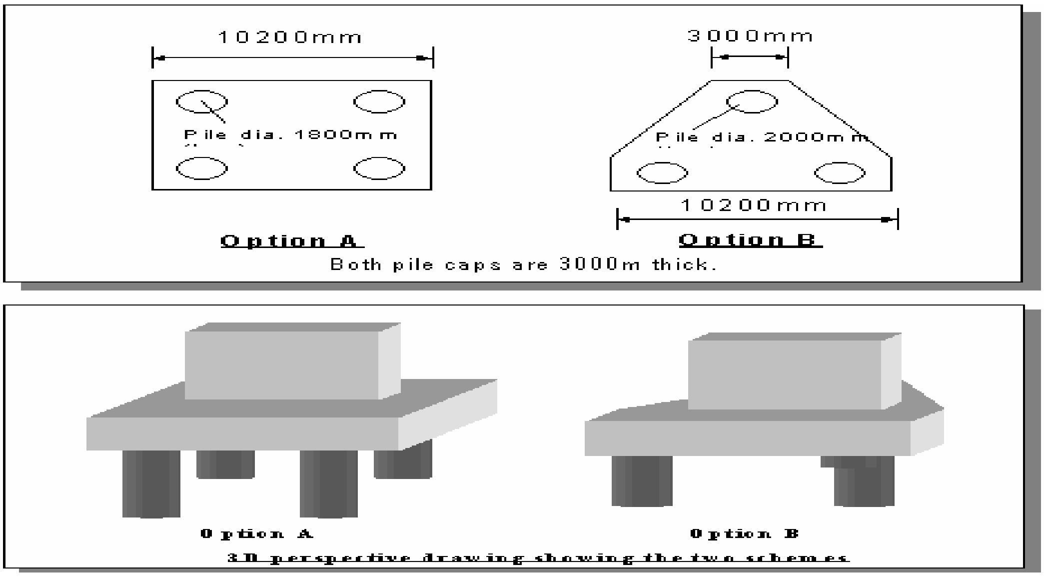
System level service	Service Name	Description/Use
User Administration	user_admin	The main page for administering user rights, including access to computational resources and other available services
System Administration	system_admin	Used for administering and managing systems services
Page Administration	page_admin	Used for page-based administration
Indicators	indicator_admin	Provides services related to constructing sustainability key performance indicators (KPIs), including updates and composition of applicable indicators on the fly.
Design Options	design_option	Used to create an instance of a design alternative for a given project. The created instances are then used for sustainability assessment (see FIGURE 7d)
Design Instances	design_opt_inst	Used to provide services to enable users create instances of design options and populate it with design configurations parameters
Project Instances	project_admin	Provides services related to creating projects and subsequent sustainability appraisal
Upload/ Download Document	upload_doc, download_doc	Uploading and downloading documents
Search	search-document search_indicator search_guidelines	Used for content and context-sensitive searches as appropriate
Update	update_document update_indicator	Used for updating documents and indicators as appropriate
Compute Sustainability Index	sustainability_index_calculation	Used for analytical computation based on different techniques including multi-criteria quantitative models, fuzzy-based credit- and scaled-scoring algorithms etc. Detailed discussion of the underpinning mathematical model and computational foundations for sustainability appraisal is not considered within the scope of this paper. Details are discussed in [Ugwu et al 2005b, c].

4.4 Description of Case Study Project & Scenario Prototype Application

This section describes the case study project and a typical scenario of sustainability appraisal using the prototype system.

4.4.1 Description of Case Study Project

The case study project involved the design of a major boundary crossing bridge to ease existing traffic congestion in HKSAR. The total length of the highway infrastructure is over 5km with estimated total project cost of over US$500Million. The case study focused on a segment of the bridge infrastructure that is over 3 kilometres, with estimated cost of more than US$300Million. This gives a unit rate of about US$100Million/km of road for Civil Engineering works. The project is driven by strong environmental considerations, being located along several environmentally sensitive receivers aggregated along various dimensions such as noise, ecosystems, culture etc. The total number of piles for a 4-pile option is more than 450 (FIGURE 6).



Key: Option A = 4-pile arrangement, Option B = 3-pile arrangement

FIG. 6: Cross-section and 3-D views of alternative pile arrangements for the case study project (source [Wong, 2004])

The estimated total volume of excavation is more than 77million cubic meter of materials. The project is suitable for detailed infrastructure sustainability study because of the very high quantities of material and other resources involved which could generate some turbulence on the adjoining ecosystem and beyond, project management complexities, the engendered challenges, and the cumulative impact of the infrastructure on the environment. Thus it gives sufficient research scope for an in-depth investigation of integrative solution to infrastructure sustainability. Some of the sustainability issue investigated using the case study project include: framework for sustainability appraisal [Wong, 2004], design process management, key performance indicators for infrastructure sustainability, multi-criteria decision models and methodology and computational foundations in sustainability appraisal, sustainability knowledge management, organisational issues in designing and constructing for sustainability including project management. These aspects will be discussed in detail in future publications.

4.4.2 Scenario Description and User Experience

Table 6 below summarises the scenario, process steps, and user experience in deploying the prototype system for sustainability appraisal and knowledge management.

TABLE 6: Scenario and process steps for sustainability appraisal and knowledge management

Process Step # & Description
Step 1- Enter Scenario Background: The objective here is to extract and input basic project data and information. These include contract sum, dimensional details, drawings, client, location, affected parties, time and duration for each stage, as well as any particular project constraints that need to be adequately addressed if they significantly affect the outcome of design options to be considered in the sustainability appraisal – Figure 7a.
Step 2 - Design Infrastructure Scheme: This is an intensive cognitive process that results in different design configurations. The design process is supported through the provision of appropriate steps [FIGS 7b & 7c] Design files can also be imported and mapped into the system using eXtensible Mark-up Language (XML) technology.
Step 3 - Prepare Engineering Analysis Sheet: After the scopes of the schemes in step 2 are defined and quantified resulting in components design configuration, the design rationale assumes that sufficient design data/information exists to facilitate sustainability appraisal. The engineering analysis sheet is used to document the differences between the design options and hence the rational and underpinnings for the design decisions (i.e. from engineering point of view), between the schemes considered. The key point in this step is that the statement must be clear and easy to understand, for future references.

Step 4: *Select Applicable Indicators for Sustainability Assessment*: This step involves accessing a data storage system (such as database management system) and selecting the set of sustainability indicators that are applicable to the project. The choice of applicable indicators may be location-specific, but one major requirement here is the flexibility to compose the indicators 'on the fly' – (FIG. 7d)
Step 5 - Enter Indicator Scoring: Based on the different schemes obtained in Step 2, an Indicators Assessment Table will be populated with data. It generally involves scores to be given against each item in the table. However, the scores will require logical analysis, as well as reasonable judgment, and for some indicators, subjective judgment (e.g. those relating to aesthetics). There is need for collaborative working amongst different specialists who are best qualified to make accurate and logical evaluation. For example, for those cost-related indicators under "Economic" category, Quantity Surveyor's involvement may be required in order to obtain professional opinion on the cost of each of the schemes concerned.
Step 6 - Assign Weights to Indicators: This step is used to assign weighting for each indicator to reflect their relative importance in the multi-criteria decision-making. The weights could be determined from the governmental policy of the country (for example in Hong Kong SAR, environmental indicators could have higher weightings than cost, also health and safety considerations may eventually override other advantages. The KPIs should be weighted proportionately for use in the multi-criteria decision analysis and decision-making model) - FIG 7e.
Step 7 - Compute Sustainability Index (a composite aggregate index from all key indicators): When all the scores and weightings are confirmed, this step involves entering the scores into the Sustainability Index score table for calculations and subsequent graphical presentation – FIG 7e.
Steps 8 - Display Results (numerical and graphical displays): After Step 7, the appraisal of the sustainability of the design schemes is considered to be complete. The scores are computed and could be displayed to the user graphically (e.g. as a ROSE diagram plot), the relative strength and weakness on each of key sustainability categories are then compared for the different schemes and design options being assessed. FIGURE 7e illustrates computational analysis for a pile design option. Decision as to which options are to be adopted would be made by senior project management level and such decisions would be facilitated by visual/graphical display of computed results. The next challenge then is to ensure sustainable construction, for example by gauging the performance of the construction stage.

4.4.3 Typical outputs

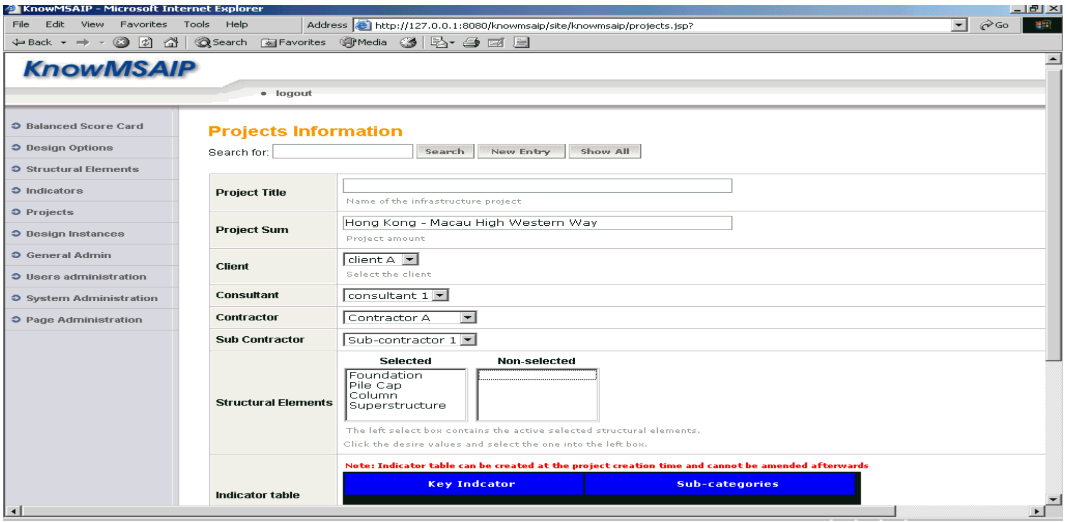


FIG. 7a: Project input interface window

Fig. 7a – 7e show the screen shots from a web-based KnowMSAIP (*Know*ledge *M*apping for *S*ustainability *A*ppraisal in *I*nfrastructure *P*rojects) prototype, illustrating some of the functionalities outlined in the framework. These services have been implemented to address identified end user requirements for sustainability appraisal. Fig. 7a demonstrates the interface for extracting and inputting project details while FIGURE 7b demonstrates information delivery to a user showing some process steps to create and populate design options for sustainability appraisal. This is an important dimension of organizational learning on infrastructure project sustainability, within a broader context of good integrated design practice.

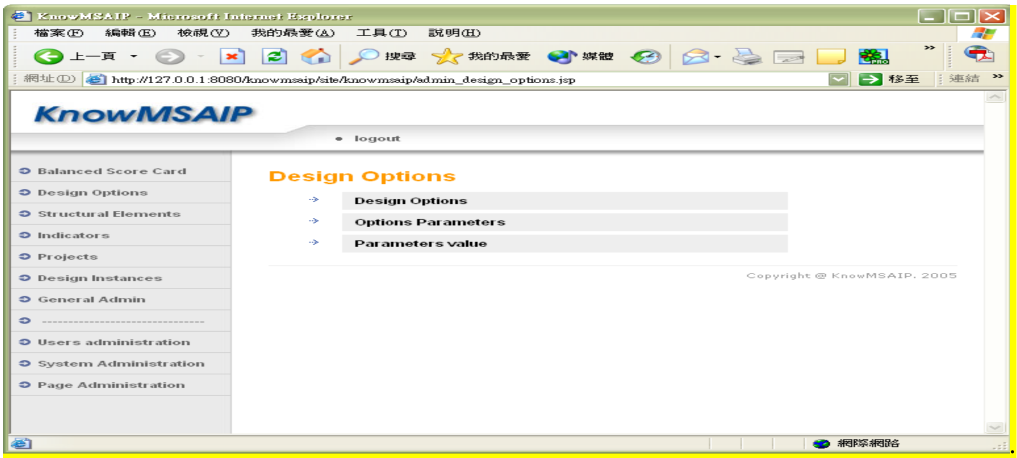


FIG. 7b: Interface showing process/sequences for creating and populating design option parameters.

Figure 7c illustrates creating an instance of a project structural element, with the associated aggregated design information content delivery to a user, while Fig. 7d shows the interface for constructing sustainability indicators applicable to projects on a case-by-case basis (i.e. 'on the fly').

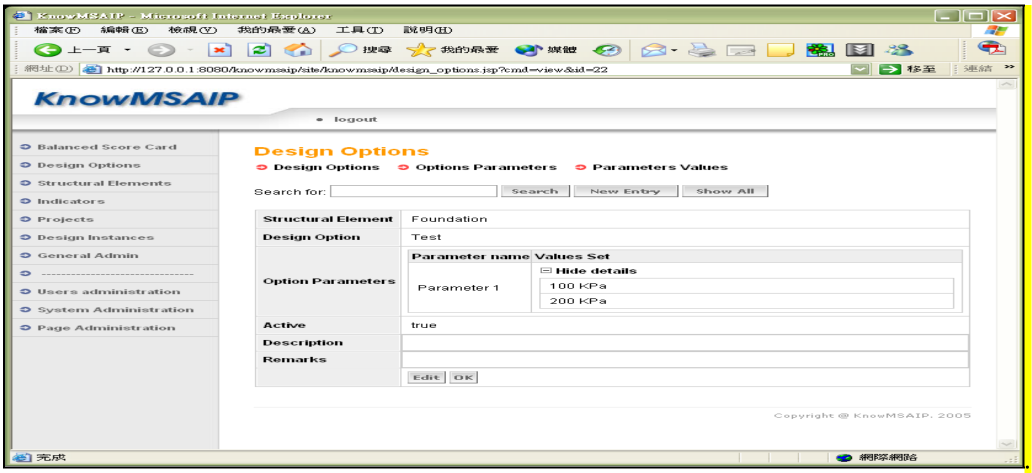


FIG.. 7c: Interface showing integrated data and information services delivery in design option creation

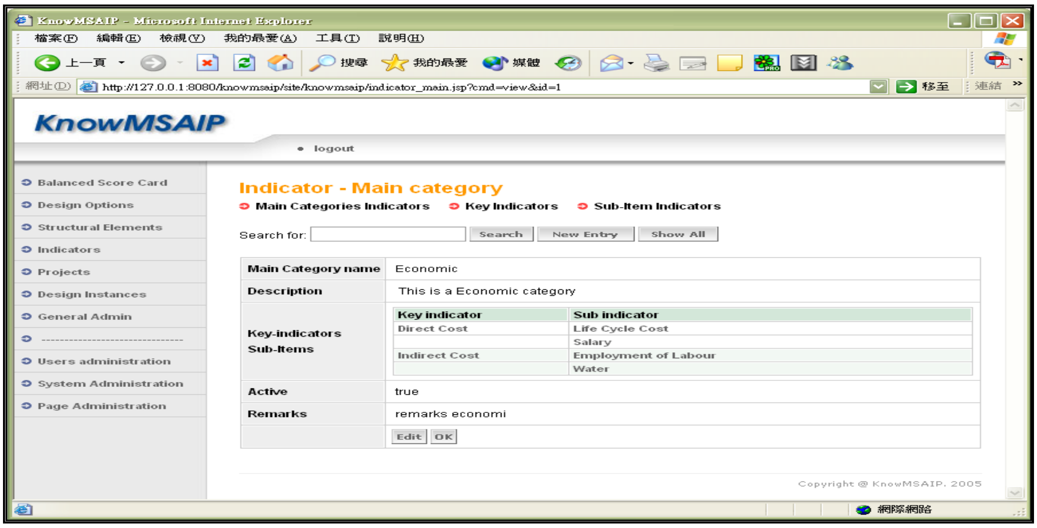


FIG.. 7d: Interface for viewing, constructing, and deconstructing sustainability indicators

Fig. 7e shows typical computations for sustainability assessment of a design option using the service '*sustainability_index_calculation*'. Other services available to users include document upload and management. The structure and content of the documents are designed to encapsulate relevant (context-specific) knowledge processes as part of wider organizational strategy for knowledge capture, storage and re-use in distributed collaborative-working environment [Uschold & Grüninger, 1996], [Butz et al, [1999], [Kerschberg et al, 2004]. The Figures below show snapshots of the pilot prototype implementation.

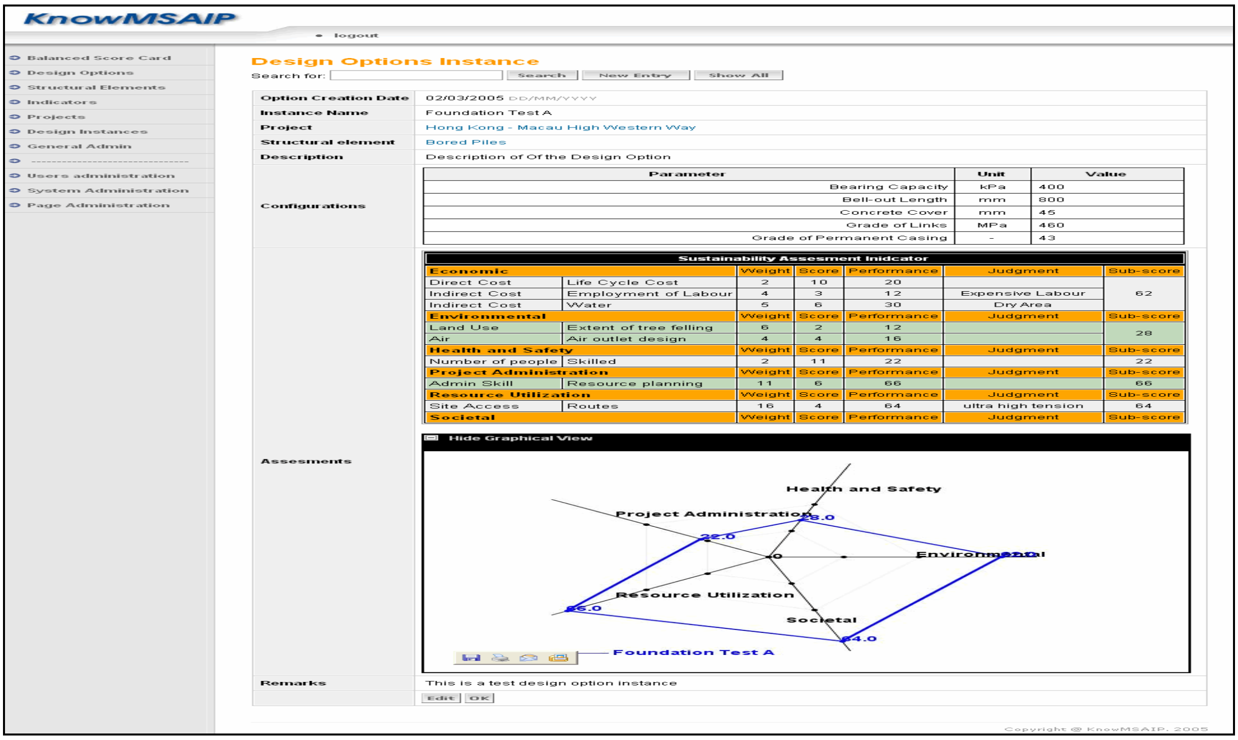


FIG. 7e: Sustainability assessment of a design option using the service: compute sustainability index (data used is for illustration only)

5. CONCLUSIONS & RECOMMENDATIONS

There has been increasing realisation in the built environment research community on the need for frameworks and tools that facilitate quantitative assessment of infrastructure sustainability, in the built environment [Ugwu, 2003], [Deakin et al, 2000a] ,[Deakin et al, 2002b]. However, a pre-requisite to developing and implementing such frameworks and tools is to understand the current state of practice in sustainability design and construction. The research reported in this paper focused on these basic requirements. The paper first discussed a survey conducted to investigate how construction organisations address sustainability including knowledge management at the organisational levels. The survey findings indicated considerable scope for improvement in several areas. The knowledge dissemination mechanisms that require significant improvement include post-project reviews, in-house seminars, mentoring schemes, on-line delivery of resources, provision of IT tools for decision-support in infrastructure sustainability appraisal and assessment, in-house guidelines, and external training programs and services (section 3). The criticality in knowledge dissemination mechanism such as post-project review indicates the need for tools that adequately capture lessons learned in a project.

Using the survey findings, the paper proposed a service-oriented framework and architecture for sustainability appraisal and knowledge management in infrastructure delivery (section 4). This is an integrated holistic approach to address the problems of sustainability design and construction in the architecture, engineering, and construction (A/E/C) sector. The proposed framework is an integrative solution that harnesses complementary computing techniques and paradigms to address the limitations in current practice. These include web-based solutions, ontology-driven intelligent search, and context-specific data, information and knowledge delivery. Thus this paper has espoused the need for integrative approach to sustainability knowledge management in infrastructure systems and project delivery. The proposed framework addresses the identified limitations of knowledge dissemination mechanisms discussed in section 3. The solution strategy is to synergistically deploy evolving state-of-the-art computing and ICT techniques and provide integrated computational, content, and context-specific knowledge management solution for improved sustainable design and construction practice in the A/E/C sector (Table 6).

There has been progression in mainstream knowledge management (KM) practice. This started with the 1st generation systems that centred on the supply side with a focus on "getting the right information to the right people at the right time". A previous study confirmed that this is the predominant current state of KM in construction [Ugwu et al 2003]. It then progressed to the 2nd generation systems that incorporate the demand side of KM. The focus here is on both knowledge production and knowledge integration at the enterprise level. The proposed framework is generic and independent of specific implementation constructs and paradigms such as the evolving web-services. Then main underpinning in the proposed framework is the need to improve micro-level sustainability appraisal and knowledge management by addressing sustainability requirements in infrastructure design, construction, and operation in an integrated holistic manner. It represents a robust way to analyse, understand and model the domain problem solving. This would facilitate cross-organisational learning and knowledge management. The service-oriented architectural framework takes a quantum leap into the evolving integrative approaches to deliver various types of knowledge services using appropriate computing and ICT techniques. This level of pervasive computing would be underpinned by rich domain taxonomy/ontology [Ugwu et al, 2003a], [Ugwu et al, 2005a],[Uschold & Grüninger, 1996]. The main thrust of this paper is been that knowledge is a critical resource and that efficient organisational knowledge management is a critical requirement to achieve the complimentary objectives of infrastructure sustainability and sustainable construction environment [Ugwu, 2005a, b c]. Thus there is a need for large-scale collaborative research to investigate suitable underpinning ontology for the problem domain. This requires joint collaborative research between academia and industry. The research reported in this paper is a contribution towards addressing this requirement in sustainability research.

6. ACKNOWLEDGEMENTS

The research reported in this paper is supported by The University of Hong Kong (HKU) through (i) Seed Funding Basic Research Grant for the project "*Know*ledge *M*apping for *S*ustainability *A*ssessment in *I*nfrastructure *P*rojects - *KnowMSAIP*" (Grant No: 10205238), and (ii) Research Incentive Award to Dr Ugwu for the project "Evolutionary Design of Bridges in Hong Kong"(Award No: 1025599). The author acknowledges the contributions of the survey respondents and others who contributed to the project-based case study and domain knowledge acquisition.

7. REFERENCES

Anumba C. J, Ugwu O. O, Ren Z (Eds), (2005), *Agents and Multi-Agent Systems in Construction*, ISBN 041535904X, SPON Press, Oxford UK, USA, and Canada..

Armour P (2003). "In the zone: the need for flexible roles", Communications of the ACM 46(5), pp 15-19, ACM Publications Office, New York.

Bierkeland J., (2002): "Design for Sustainability: a Sourcebook of Integrated Ecological Solutions",

BREEAM (Building Research Establishment Environmental Assessment Method), (2004) URL: http://products.bre.co.uk/breeam/index.html

Butz A., Hollerer T., Feiner S., MacIntyre B., and Beshers C (1999). "Enveloping users and computers in a collaborative 3D augmented reality. In Proc. Int. Workshop on Augmented Reality (IWAR) '99, San Francisco, CA, October 20—21, 1999, available from URL: http://csdl.computer.org/comp/proceedings/iwar/1999/0359/00/03590035abs.htm (last accessed 18 March 2005)

CERT (1999): *HK-BEAM (New Offices) – An Environmental Assessment for New Office Designs*, Version 1/96R, ISBN 962-85076-2-1, Centre of Environmental Technology, Limited (CERT), Hong Kong.

Chen X, Li J, Zhou N., (1999): Spatial Information Systems Applications for Sustainable Development", Geoinformatics and Socioinformatics, The Proceedings of Geoinformatics 99 Conference, Li et al (eds.) Ann Arbor, 19-21 June 1999, pp 1-8.

Deakin M, Curwell S. R., Lombardi P (2002a), 'Sustainable Urban Development: The Framework and Directory of Assessment Methods', Journal of Environmental Assessment Policy & Management, 4 (2), 171–197

Deakin M, Lombardi P, Mitchell G (2002b), 'Urban Sustainability Assessment: a Preliminary Appraisal of Current Techniques', Urbanistica, 118, 50-54 Earthscan Publications Ltd, London, UK, ISBN 185383 897 7 / 185383 9000 0

Government of Hong Kong SAR, SUDEV21 (Sustainable Development for the 21st Century), (2004)URL: http://www.susdev.gov.hk/html/en/council/

GRI (Global Reporting Initiatives), (2005) URL: http://www.globalreporting.org

Kerschberg L., Chowdhury M., Damiano A., Jeong H., Mitchell S., Si J, and Smith S (2004), "Knowledge Sifter: Ontology-Driven Search over Heterogeneous Databases," International Conference on Scientific and Statistical Database Management (SSDBM) 2004, Santorini Island, Greece, 2004, available form URL: http://eceb.gmu.edu/pubs/Kerschberg_KS_SSDBM.pdf (last accessed 18 March 2005)

Khalfan M. K, Bouchlagehm D. M, Anumba C. J, Carrillo P. M (2002): "A Framework for Managing Sustainability Knowledge – the C-Sand Approach", Proceedings of eSm@rt 2002, 19-21 November, 2002, Salford UK,

Morikawa R., Kerschberg L., "MAKO: Multi-Ontology Analytical Knowledge Organization based on Topic Maps," *Fifth International Workshop on Theory and Applications of Knowledge Management*, Zaragoza, Spain, 2004, available form URL: http://eceb.gmu.edu/pubs/Morikawa_Kerschberg_TAKMA.pdf (last accessed 18 March 2005)

Nahar, N., Al-Obaidi Z, Huda N (2001). Knowledge Management in International Technology Transfer. In D. F. Kocaoglu, T. R. Anderson, D. Z. Milosevic. T. U. Daim, K. Niwa, T. R. Gullegd, C. Kim & H. Tschirty (Eds.) Technology Mamangemnt in the Knolwedge Era. IEEE and PICMET, Oregun, USA, pp 355-364, IEEE ISBN: 0-7803-6702-2 & PICMET ISBN: 1-890843-05-9

Newel, A., (1982): "The Knowledge Level", *Artificial Intelligence*, 18(1), pp 87-127

Nonaka I, Toyama R (2002): "A Firm as a Dialectical Being: Towards a Dynamic Theory of a Firm", *Industrial and Corporate Change*, 11(5), pp995-1009, ICC

Nonaka I, Toyama R, Konno N., (2000): "SECI, Ba and Leadership: a Unified Model of Knowledge Creation", *Long Range Planning* 33 pp 5 –34, Elsevier Science

Odysseus M (2003): "Using Sustainability Related Criteria in Construction Support Systems", *Proceedings of 2nd, International conference on Construction Innovation and Sustainability in the 21st Century*, Hong Kong, 12-15 December 2003 (CD Rom).

Saaty T. L (1977), 'A Scaling Method for Priorities in Hierarchical Structures', Journal of Mathematical Psychology, 15(3), 234-281

Saaty T. L (1980), *The Analytic Hierarchy Process*, New York, McGraw-Hill

SDU – Sustainable Development Unit - HKSAR (2003): Council for Sustainable Development, "Formulating Sustainable Development Strategy for Hong Kong" Policy paper No 03/03, Available from: http://www.susdev.gov.hk/text/en/su/index.htm

Snowden D., (2002): "The New Simplicity: Context, Narrative, and Content" Knowledge Management 5 (10), pp 11-15, ISBN 1369-1368, Arkgroup, UK.

Triantaphyllou E, Lootsma F. A, Pardalos P. M, Mann S. H (1994), 'On the Evaluation and Application of Different Scales for Quantifying Pairwise Comparisons in Fuzzy Sets', Journal of Multi-Criteria Decision Analysis 3(3), 133-155

U.S Green Building Council, LEED (Leadership in Energy and Environmental Design) Green Building Rating System, (2004) URL: http://www.usgbc.org/leed/leed_main.asp

Ugwu O. O (2005): "Knowledge as a Critical Resource in Managing Environmental Impacts of Construction"**,** *Keynote Address* delivered to CIBW99 Working Commission 4th Triennial International Conference - "Rethinking and Revitalizing Construction Safety, Health and Quality", 17-20 May, 2005, Port Elizabeth - South Africa.

Ugwu O. O**,** Anumba C. J. Newnham, L, Thorpe A; 1999: Applications of Distributed Artificial Intelligence (DAI) in the Construction Industry, October 1999, ISBN 1 897911 16 5**.**

Ugwu O. O, Kumaraswamy M. M, Wong A., (2003a) "A Taxonomy for Measuring the Sustainability of Construction Projects", *Proceedings of 2nd International conference on Construction Innovation and Sustainability in the 21st Century*, Hong Kong, 12-15 December 2003 (CD Rom).

Ugwu O. O, Ng S. T, Kumaraswamy M. M., 2003b: "Key Enablers in IT Implementation – A Hong Kong Construction Industry Perspective", in *' Towards a Vision for Information Technology in Civil Engineering*', *Proceedings of 4th Joint International Symposium on Information Technology in Civil Engineering* (Flood I, Ed**.**), Nashville, Tennessee USA, 15-16 November 2003, Sponsored by ASCE's Technical Council on Computing Practices and European Group for Intelligent Computing in Engineering (EG-ICE), ISBN 0-7844-0704-5

Ugwu O. O**.** (2003). "Book Review*:* Red Man, Green Man: Performance Indicators for Urban Sustainability", (David Fell, Jayne Cox, and Mark Thurstain-Goodwin - Authors), 1st Edition, 2002, 58pp, *Journal of Building and Construction Management*, 8**(**1), pp 60-61, **I**SSN 1024-9540.

Ugwu O. O., Kumaraswamy M. M., Ng S. T, Paleneswaram E., Rahman M.M, Poon S. W, Lo V (2005a): "Intelligent Information Delivery Maturity Model for Integrating SMEs in Construction Supply Chains" Proceedings of CIBW99 Working Commission 4th Triennial Conference - "*Rethinking and Revitalizing Construction Safety, Health, Environment and Quality*", pp 29-48, 17-20 May, 2005, Port Elizabeth - South Africa

Ugwu O. O., Kumaraswamy M. M., Wong A, Ng T (2005b): "Sustainability Appraisal in Infrastructure Projects (SUSAIP): Part 1 – Development of Indicators and Computational Methods" *Automation in Construction*, (in press), available online from http://www.sciencedirect.com

Ugwu O. O., Kumaraswamy M. M., Wong A, Ng T (2005c): "Sustainability Appraisal in Infrastructure Projects (SUSAIP): Part 2 – A Case Study in Bridge Design" *Automation in Construction*, (in press), available online from http://www.sciencedirect.com

UN (United Nation) (2002): 'Report of the World Summit on Sustainable Development', Johannesburg, South Africa, 26 August - 4 September 2002, United Nations New York, 173 pp

UNCED 1992: United Nations Conference on Environment and Development (UNCED), 1992, *Agenda 21*.

Uschold, M., Grüninger M., (1996). "ONTOLOGIES: Principles, Methods and Applications" *Knowledge Engineering review* 11(2), pp. 93-155.

WCED 1987: World Commission on Environment and Development (WCED). 1987. *Our Common Future*, Oxford, Oxford University Press

Wong A (2004), 'A Framework for Measuring the Sustainability of Infrastructure Projects', MSc Thesis, The University of Hong Kong, HKSAR, 300pp.

Zhou L, Lowe D. J (2003): "Economic Principles of Sustainable Construction", in *Proceedings of 2nd, International conference on Construction Innovation and Sustainability in the 21st Century*, Hong Kong, 12-15 December 2003 (CD Rom).