E-Society Portal: Integrating Urban Highway Construction Projects into the Knowledge City

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Abstract: Community involvement is an important factor for sustainable highway construction. Information and communication technologies provide a new and more effective approach to facilitate community involvement. However, there are too many parameters with conflicting and subjective definitions related to sustainability and too many stakeholders with varying degrees of interest and sophistication. There is a need for an effective tool to communicate project impacts on sustainability to local communities. This paper presents an ontology for stakeholder management and sustainability in highway construction. An ontology is a conceptual semantic model that attempts to capture human knowledge (both explicit and tacit) in a consistent manner. Ontologies include three main elements: a taxonomy (common vocabulary presented in concept trees), set of relationships (linking concepts across trees), and axioms (limitation/constraints on the behavior of concepts). The ontology was used to develop a portal for broadcasting highway design features to local communities. By browsing through the portal, a user can learn about project elements, the impacts of each element on sustainability issues, who is sponsoring such element, and what efforts have been made to reduce any impacts of such elements on local communities.

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Introduction

The city of tomorrow is shaped as a knowledge city that promotes progressive and integrated knowledge culture. This culture incorporates three overlapping spheres: achieving competitiveness through knowledge industries (products); empowering citizens to create, share, evaluate, and renew knowledge in all aspects of life; and integrating sustainability in urban form as means for preserving natural resources and enhancing the socioeconomic quality of life for citizens. The main characteristics of a modern knowledge city include (Ergazakis et al. 2004):

- Provision of access to new communication technologies for all citizens;
- Research excellence which provides a platform for knowledge-based goods and services;
- Provision of instruments to make knowledge accessible to citizens;
- Ability to generate, attract, and retain highly skilled citizens in different domains;
- Provision of efficient, dependable, and cost competitive access to infrastructure to support economic activity;
- An urban design and architecture that incorporate new technologies;
- Responsive and creative public services; and
- Economy with enough critical mass to support world competitive specialization.

It is important to distinguish here between knowledge and information. Knowledge consists of facts, truths, and beliefs, perspectives and concepts, judgments and expectations, methodologies and know-how. Knowledge is accumulated and integrated and held over time to handle specific situations and challenges. Information consists of facts and data organized to describe a particular situation or condition (Ackoff 1989).

A knowledge city is achieved mainly through active citizens, NGO (nongovernment organizations), and private sector contribution to the achievement of sustainable knowledge economy within a conducive culture and business environment set up by city leaders. Consequently, in a knowledge city, virtually all urban projects are commissioned through active participation of citizens.

Traditional CI (community involvement) methods focus on informing local community with project options and impacts through community surveys (using interviews or mailed questionnaires), flyers, newsletters, public meetings, workshops, and project web pages. In general, these methods provide for a unidirectional exchange of information (mainly from city officials to community). Such methods have the following drawbacks:

- There are too many parameters with conflicting and subjective definitions;
- There are too many stakeholders with varying degrees of interest and sophistication; and
- Hypertext information does not provide effective tool to ad-

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dress all concerns and customize the information to the specific needs of stakeholders.

In the context of knowledge city, CI is achieved through a two-way exchange of knowledge (in contrast to information exchange). Communities of interest (local government, residents, business owners, NGOs, and interested stakeholders) can exchange ideas, design options, assessment of impacts; vote on different design schemes; collaborate on the development of new design options; and even promote the project to developers.

A more effective system is required to realize a knowledge-enabled CI portal. Semantic systems (ontology-based systems) are an effective means to capture the fragmented multidisciplinary knowledge that lies at the intersection of construction and sustainability. Such systems are becoming the state-of-the-art in the knowledge management arena (Fensel 2001). An ontology is "a logical theory which gives an explicit, partial account of a conceptualization (Guarino et al. 1995)." The conceptualization is basically an idea of the world that a person or a group of people can have (Corcho et al. 2003).

It is important to point out here that citizens in knowledge cities are knowledge savvy. They possess enough knowledge management (KM) acumen to actively participate in criticizing project designs, compose new ideas, and vote on designs in an informed way. A knowledge-enabled portal for community involvement clearly and efficiently provides means to:

- Capture the needs of every stakeholder during the provision of new projects;
- Draw on the expertise of all relevant stakeholders. This is becoming more relevant given the increasing role of nontechnical issues in urban project development. Moreover, in a knowledge city, community members are expected to possess and to be able to communicate valuable innovative ideas;
- Document the rationale and consequence of each decision (for future data mining);
- Empower citizens with enough information and means to study, comment, propose, and evaluate creative solutions and design alternatives; and
- Provide local communities and business with a clear perspective of the short- and long-term impacts of a new project on the environmental, social, and economic sustainability. This will allow local business to integrate new project in their future plans.

An ontology is the cornerstone of any effective collaborative KM system in a multifaceted domain such as CI (Fensel 2001). This paper presents an ontology for stakeholder management and sustainability in the domain of urban highway construction (S2HOnto). This ontology was utilized to develop a prototype e-society portal: a semantic system to support knowledge-enabled community involvement in the design of new highways (within urban settings).

Sustainable Construction and Urban Engineering

Construction industry is a major player in the development of infrastructure that defines urban landscape and facilitates social and economic interactions amongst urban habitat. In many cases, these infrastructure systems have been commissioned in ways that could have negative impacts on the environment. A fundamental need for our communities in the 21st century is to engineer our urban developments in a sustainable manner. This includes analysis of the impacts of new projects on the environment, local communities, and the economy.

Sustainable construction practices have been defined by a multitude of researchers. These definitions can be categorized into three main areas.

1. *Environmental efficiency:* This includes prudent use of natural resources (DETR 2000); maximization of resource reuse (Kibert 1994); reducing the use of the four generic resources used in construction, namely, energy, water, materials, and land, at each stage in the project life cycle (Kibert 1994); create a healthy and nontoxic environment through the elimination or careful and managed use of hazardous and toxic products in the indoor and exterior built environment (Kibert 1994); extract fossil fuels and minerals, and produce persistent substances foreign to nature, at rates which are not faster than their slow redeposit into the Earth's crust (Robšrt 1995); minimize damage to sensitive landscapes, including areas which are valuable from a scenic, cultural, historical, or architectural point of view, and minimize intrusion into wilderness areas (Hill and Bowen 1997).

2. *Social impacts:* This includes improving the quality of human life by ensuring secure and adequate consumption of basic needs, which are food, clothing, shelter, health, education, and beyond that by ensuring comfort, identity, and choice (Yap 1989); making provision for social self-determination and cultural diversity in development planning (Gardner 1989); ensuring that the operation of development (after the construction process is complete) is compatible with local human institutions and technology (Yap 1989); protect and promote human health through a healthy and safe working environment; plan and manage the construction process to reduce the risk of accidents, and carefully manage the use of substances which are hazardous to human health (Hill and Bowen 1997); seek fair or equitable distribution of the social costs of construction and, where this is not achieved, determine fair compensation for people adversely affected by construction operations (Hill and Bowen 1997);

3. *Economic development:* This includes maintaining high and stable levels of economic growth and employment (DETR 1999); provide flexible design to reduce life-cycle cost of a project; promote employment creation and, in some situations, labor intensive construction for disadvantaged communities as this should result in a significant portion of the financial contribution of a project remaining and circulating in local hands (Hill and Bowen 1997); minimization of intrusion into intensive-operation area of farm, high-investment areas of other business and viable agriculture field; use full-cost accounting and real-cost pricing to set prices and tariffs, for goods and services, that fully reflect social and biophysical costs (Hill and Bowen 1997).

Research Scope and Metholodgy

The main objective of this research project is to develop and implement the technologies of semantic web (ontology-based systems) to support a two-way exchange of sustainability knowledge (as it pertains to highway design and construction) between local officials and stakeholders. The deliverables of this research are:

- Capturing sustainability and stakeholder management issues (both explicit and tacit) into a representative domain ontology for stakeholder management and sustainable highway construction.
- Linking highway design features to the proposed ontology. What are the construction components/activities that could have a bearing on sustainable development? How and where can we safeguard sustainability during highway design, construction, and operation?

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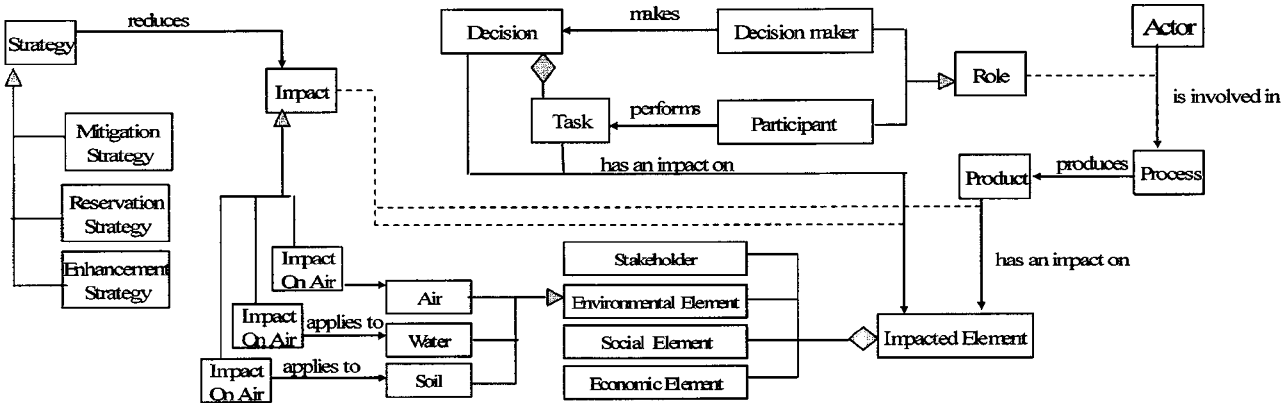

Fig. 1. Abstract ontological model

- Establishing a prototype knowledge-enabled portal for community involvement in highway design.

It is important to distinguish here between an ontology and a knowledge base. An ontology models the fundamental structure of knowledge in a domain, on top of which a knowledge base can be created. i.e., ontology provides a theory of the knowledge concepts and their interrelationships, while a knowledge base uses such concepts to record cases or information about real cases.

It is tempting, therefore, to think of ontologies as universal theories of our conceptualization regarding a domain. They are not. No single ontology can encapsulate the wide spectrum of tacit and explicit human knowledge in one domain. In fact, postmodern organizations of knowledge can no longer seek universality in their scope (Mai 1999). To that end, Steimann (2000) presented 15 different ways organization use to represent the concept of *"role."* Ontologies should be considered as fuzzy artifacts that evolve over time and can never encompass a universal view of all the linguistic, cultural, temporal, and organizational aspects of human knowledge (Lenat 2001; Durusau and Newcomb 2004).

This research, as many in the ontology development domain (for example, López et al. 1999; Pinto and Martins 2001; Devedzi 2002), has only attempted to develop one (of many possible) ontology for stakeholder management and sustainability in highway construction. Future ontologies can expand or complement the proposed ontology using some ontology integration techniques (ontology mapping, fusion, merger or topic mapping). Such distributed/evolutionary approach is becoming the state-of-the-art in ontology development (Maedche et al. 2003).

With the lack of standard methodology for ontology development, the research followed the guidelines proposed by Uschold and King (1995), Gómez-Pérez et al. (1996, 1998), Gómez-Pérez and Rojas (1999), Grüninger et al. (1997), and Maedche (2002) for the development of the ontology:

- Literature review: this covered reviews for related domains, including sustainable development and sustainability in construction (and in highway construction in particular). The reviews also included analysis of best practices in the following domains: knowledge management, semantic web, and ontology.
- Specifications: collect concepts related to sustainability in the construction industry especially in highway construction presented in IDEF0 (integrated definition method-function modeling) diagrams.
- Classification: organize concepts in class hierarchies (taxonomies).
- Implementation: transforming entities and their relationships into OWL (Web ontology language), the de facto standard in ontology programming.
- Validation: using competency questions, expert survey, and document search to validate the ontology.

Ontology of Sustainability in Highway Construction

The proposed ontology has the following main concepts/domains (each is the root of a taxonomy): *Entity* (including *Project*, *Process*, *Product*, *Actor*, and *Resource*), *Mechanism*, *Constraint*, *Basic Concept*, *Ontological concept*, and *Technical Topics*. Any project (e.g., renovation of a street, construction of a new street, a new transit system) produces a set of products (e.g., new lanes, new bridge, dedicated lanes, transit tracks, new traffic patterns, and signals). Each of these products has a set of possible design options. The options are developed through a set of interlocked processes, where actors (e.g., design firms, department of transportation) make decisions (e.g., set project objectives, develop options, configure options, and approve an option). Each option has a set of impacts (Technical Topics) on various sustainability elements, such as health hazards, increased user cost, negative impacts on local business, and enhancement to traffic flow. These elements include stakeholders (Actor), such as a business, or a community group, basic environmental elements (Technical Topics), such as air, water, and soil. For each of these impacts, a set of strategies (Technical Topics) could be used to reduce any negative consequences on the impacted elements (see Fig. 1).

The ontology is process-centered (Grüninger et al. 1997) and has the following features:

- A *Process* needs *Input*, including the completion of all proceeding processes, the availability of required approvals, the availability of required knowledge items (documents, software, etc.), the availability of required *Resource* (materials, equipment, etc.), the availability of required *Actors*, and the availability of required budget.
- A *Process* has an *Output* that includes: an update to *Product time-line*, an update to the *Project schedule*, an update to the *Project budget.*
- A *Process* utilizes some *Mechanism* to support its operation. These include *Theoretical foundations* (to build a metaphorical model of the process), *Parameters*, *Technique*, *Measures*, and *Abstract concepts*.

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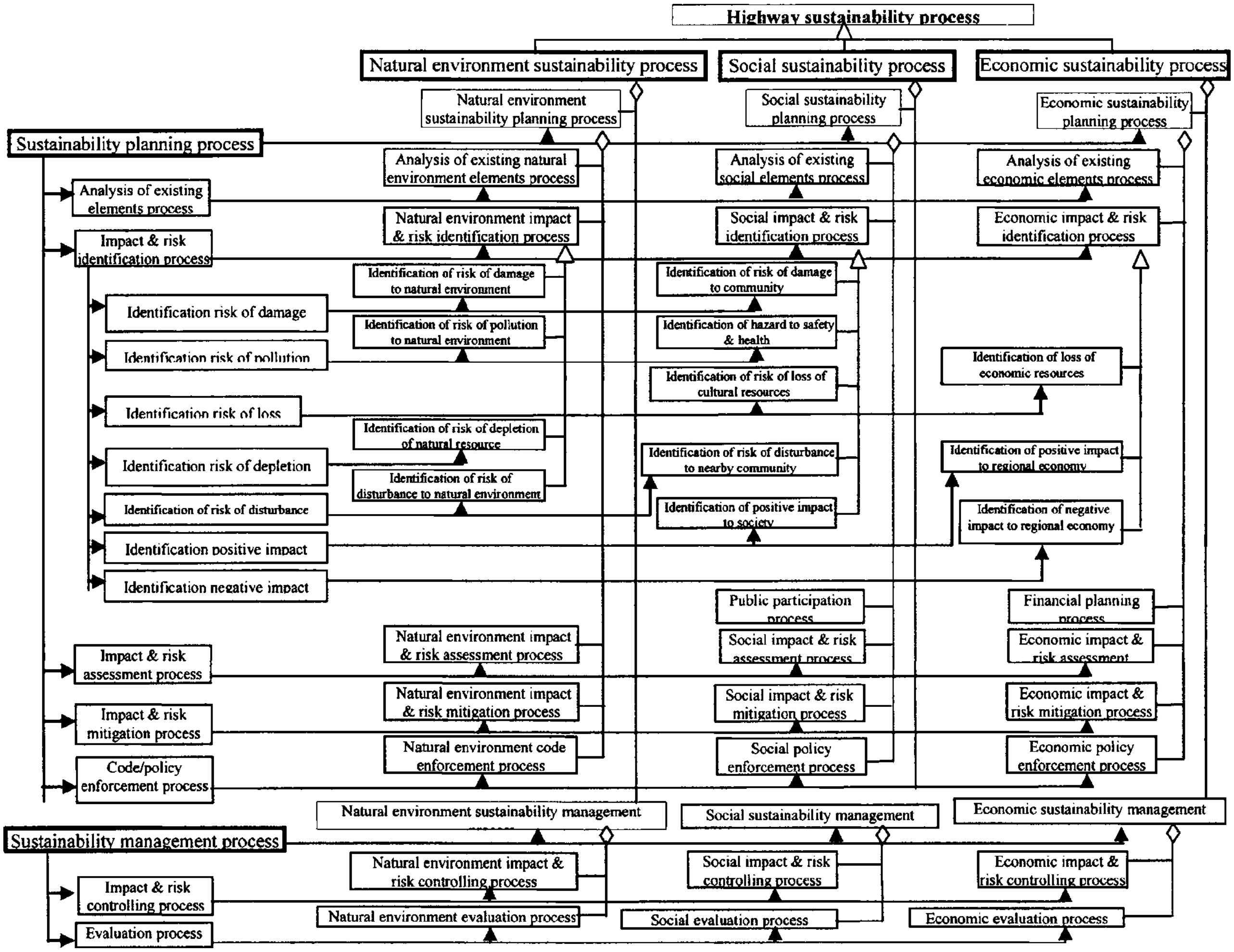

Fig. 2. Typical process matrix

- A *Process* is influenced by *Controls* as well, such as law, code, specifications, user requirements, environmental controls, and social controls.
- Ontological concepts define temporal and logical characteristics of a process or a product (e.g., *at conceptual stage, dormant, in progress*, and *completed*).
- Basic concepts define some elementary elements, such as day, month, and year (needed to describe duration).

It is not feasible to list all possible ontology concepts in this paper. The following sections provide an abstract illustration of the concepts included in the ontology. The Appendix shows an extended view of one of the main concepts: Process.

Process

Each *Sustainability process* consists of two major phases: planning and management. Each phase is subdivided into subprocesses. For example, Sustainability planning process encompasses five major subprocesses: Analysis of existing elements process, Impact and risk identification process, Impact and risk assessment process, Impact and risk mitigation process, and Code/policy enforcement process. On the other hand, three themes of sustainability: Natural environment, Society, and Economy, have to be taken into account during any *Sustainability process*. Therefore, a matrix is formed with the columns representing the three themes and the rows representing the two phases. The first-level subprocesses of the highway sustainability optimization process are shown in the matrix in Fig. 2. Each Planning process includes the following subprocesses: analysis of existing systems, identification of risks, risk assessment, development of risk mitigation tools, and code compliance check. Each management process includes two subprocesses: development of risk/impact controls and evaluation process. For instance, the *Analysis of existing natural environment elements process* is at the intersection of (derived from) the *analysis of existing elements process* and *natural environment sustainability process*. This is because it covers both domains of knowledge: looking at existing conditions (in contrast to future/suggested conditions) and only considering the environmental aspects of these conditions (in contrast to social and economic aspects).

A summary of the sustainable construction process is presented here as a sample of concept semantics as modeled in the ontology. The process of sustainable construction includes three main subprocesses.

1. *Natural environment sustainability process:* This process aims to study and analyze the natural environment through optimal use of natural resources and minimization of pollution and damage to the natural environment. *Natural environment sustainability process* includes two main sub-processes: *Natural environment sustainability planning* and *Natural environment sustainability management*.

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- *Natural environment sustainability planning process* involves many initial analyses and identification activities which aim to provide the existing natural environment element analysis and potential impact and risk identification of a highway project. This process consists of five major subclasses: *Analysis of existing natural environment elements process*, *Natural environment impact and risk identification process*, *Natural environment impact and risk mitigation process, Natural environment impact and risk assessment process*, and *Natural environment code enforcement process*.
- *Analysis of existing natural environment elements process:* analysis of existing environmental elements before project design and construction, including soil, water, and air test processes, analysis of existing climate, energy, habitat, noise, natural environment sensitive areas, etc.
- *Natural environment impact and risk identification process*: a broad analysis of the potential impact and risks of project activities with a view to identifying those which are worthy of a detailed study.
- *Natural environment impact and risk mitigation process*: investigate sustainability strategy to avoid environmental impact, to reduce environmental risk, and to provide alternatives to the construction project (Abaza 1992).
- *Natural environment impact and risk assessment process*: combining environmental loss and gains with economic costs and benefits to produce a complete account of each project alternatives or mitigations.
- *Natural environment code enforcement process*: help project planner evaluate the potential impact and risk which the construction project may have on the natural environment.
- *Natural environment sustainability management process* emphasizes how to implement a natural environment sustainability plan including actual sustainability-oriented controlling and evaluation processes. Therefore, *Natural environment sustainability process* includes two major subclasses: *Natural environment impact and risk controlling process*, and *Natural environment evaluation process*.
  - *Natural environment impact and risk controlling process* is used to monitor the actual natural environmental impact produced during construction, operation, maintenance, and even demolition phases in order to avoid and minimize this impact and risk based on the original sustainability plan.
  - *Natural environment evaluation process* is intended to determine the extent to which the project's natural environment sustainability objectives have been realized and to draw lessons from the experience gained in implementing it for use in future projects (Abaza 1992).

2. *Social sustainability process:* This process aims to enhance the livability of communities by reducing the impact and disturbance to the community and improving human safety and health. Social sustainability process consists of the following two major subclasses:

- *Social sustainability planning process*: the process concerned with the existing social element (e.g., population structure, community and neighborhood association) and potential impact and risk which the construction project may have on the nearby community and the whole society. This process includes the following subclasses: *Analysis of existing social elements process, Social impact and risk identification process, Public Involvement process, Social impact and risk mitigation process, Social impact and risk assessment process, and Social policy enforcement process*.
- *Social sustainability management process*: controlling and evaluating the implementation of social sustainability plans during the actual construction, operation, maintenance, and demolition stages of construction projects. This process includes two major subclasses, specifically *Social impact and risk controlling process and Social evaluation process*.

3. *Economic sustainability process:* This process encompasses a series of processes which enhance economic productivity by optimizing the total investment (maximizing the benefit and minimizing the cost over the life cycle of a project) and by providing the flexibility to adapt to changing need (Abaza 1992). On the other hand, Economic sustainability process also concerns itself as to how to ensure financial affordability for the project itself. Similar to Natural environment sustainability process and Social sustainability process, Economic sustainability process also includes two main subclasses: *Economic sustainability planning process and Economic sustainability management process.*

- *Economic sustainability planning process*: This process takes account of how to analyze the existing economic element and identify the potential impact on economic development, as well as how to assess this impact and risk considering long-term economic benefits. Economic sustainability planning process includes six major subclasses: *Analysis of existing economic element process, Economic impact and risk identification process, Economic impact and risk mitigation process, Financial planning process, Economic impact and risk assessment process, and Economic policy enforcement process*.
- *Economic sustainability management process*: It aims to monitor the implementation of selected actions for economic sustainability during project development, as well as to ex-post evaluate as to what extent the project's economic principles have been accomplished. Therefore, Economic sustainability management process consists of two main subclasses: *Economic impact and risk controlling process and Economic evaluation process*.

Actor

Actor defines the major players in an urban highway construction project, which includes two major subclasses: *Personnel* and *Organization:*

- *Personnel* are individual persons. It includes four subclasses: Administrator, Professional Staff, Labor (including Skilled Workers and Unskilled Workers), and Stakeholder.
- *Organization* includes four subclasses: *Enterprise*, *Government Organization*, *Nongovernment Organization* and *International Organization*.

Some of these actors can assume the role of "Stakeholder" or "Consultant." The "Stakeholders" actor into three categories:

- Impacted: individuals or organizations which are impacted by the development project;
- Interested: individuals or organizations that are not directly impacted by the project, but are still interested to get involved in the development process; and
- Responsible: actors who have some degree of responsibility or liability in regard to the development project, such as city officials, health officials, and developers.

Fig. 3 shows an abstract stakeholder-centered view of the ontology. This view illustrates the relationships between main CI processes (such as the process of stakeholder involvement design,

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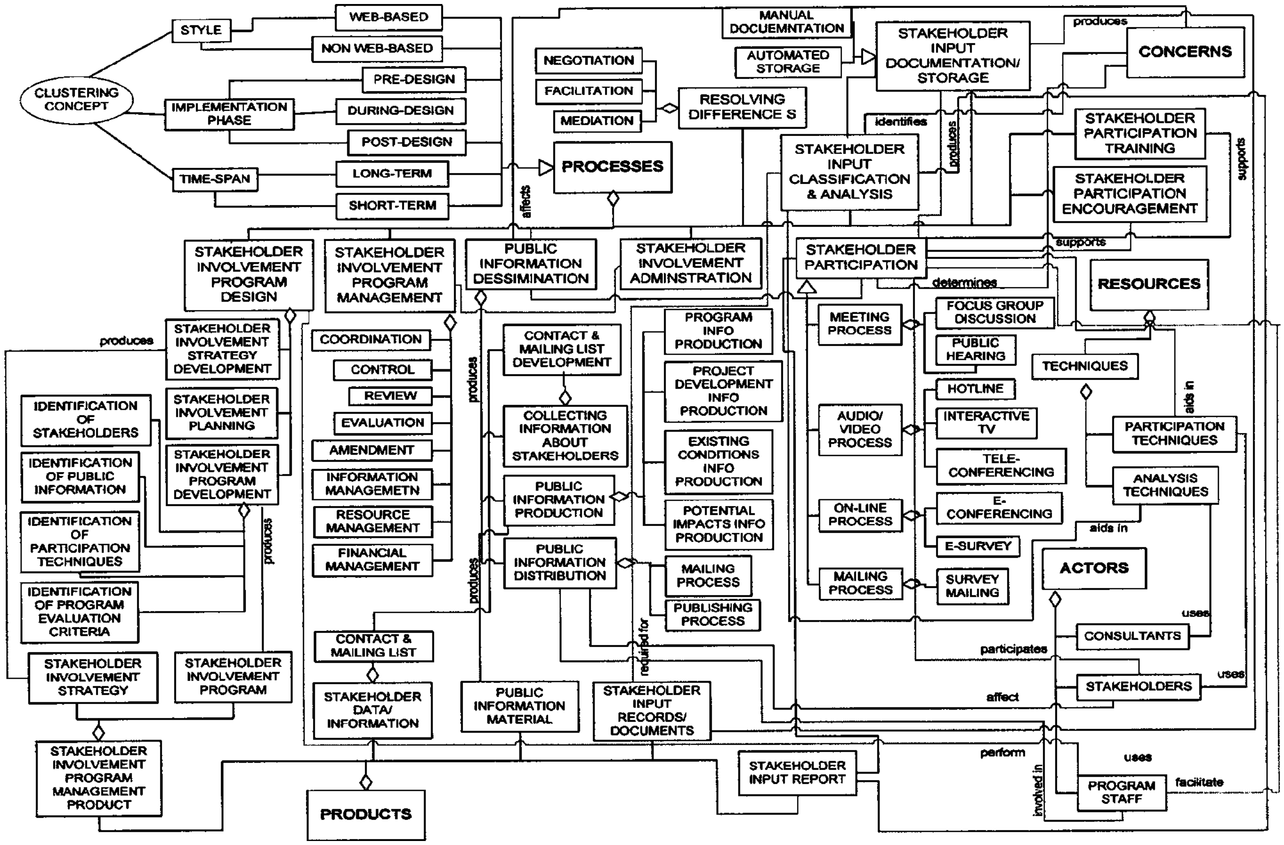

Fig. 3. Overview of stakeholder model

information dissemination, and the process of actual stakeholder participation) and the products that are produced from some of these processes (which are also used as input to other processes). The view also illustrates the relationships between the various types of CI tools (such as public meeting and project web site) and the actors involved, stakeholder concerns, and the resources needed.

Product

This domain lists all related (physical and logical) products. The physical products include bridges, tunnels, roads, and barrier walls. The logical/management products include description of the outputs of managerial processes. For example:

- *Sustainability report* includes *Analysis reports* and *Assessment reports* which are produced during the analysis of existing element processes and impact & risk assessment processes. The *Analysis of existing social element process* will produce *Community analysis report*, and *Natural environment impact and risk assessment process* will produce a series of *Natural environment assessment reports*, such as *Air pollution assessment report*, *Lighting pollution assessment report*, *Noise assessment report* and *Energy report*, etc.
- *Impact studies* include the outputs of natural environmental, social, and economic impact and risk identification processes, such as *Environmental impact studies*, *Social impact studies*, and *Economic impact studies*.
- *Environmental permit* is an intermediate product which is produced during an environmental assessment process and required by an environmental law in order to emit or discharge a pollutant or engage in certain regulated activities.

Resource

Resource domain captures those concepts required to undertake various construction processes. *Resource* includes five major subclasses: *Material*, *Personnel*, *Equipment*, *Subcontractors*, and *Software*. For example, the category for sustainability software includes *Athena*, *BDA*, *DOE*, *Energy-10*, *LISA*, *SPATACUS*, and *BEES*.

Mechanism

The research team divided the *Mechanism* domain into the following subdomains (see Fig. 4):

- *Theoretical foundations*: guidelines and instructions for building a theoretical metaphor for our entities. It includes four major subdomains: *Theories* (e.g., *theory of architecture*), *strategies* (e.g., *least energy strategy*), *Policy* (e.g., national environmental policy) and *Algorithm* (e.g., traffic allocation algorithm).
- *Abstract concepts*: fundamental not-easy-to-measure (fuzzy) concepts such as stakeholder motive, comfort level, aesthetic.
- *Parameters*: measurable elementary constructs used to formulate theories, such as emission rate, process duration, and loading factor.

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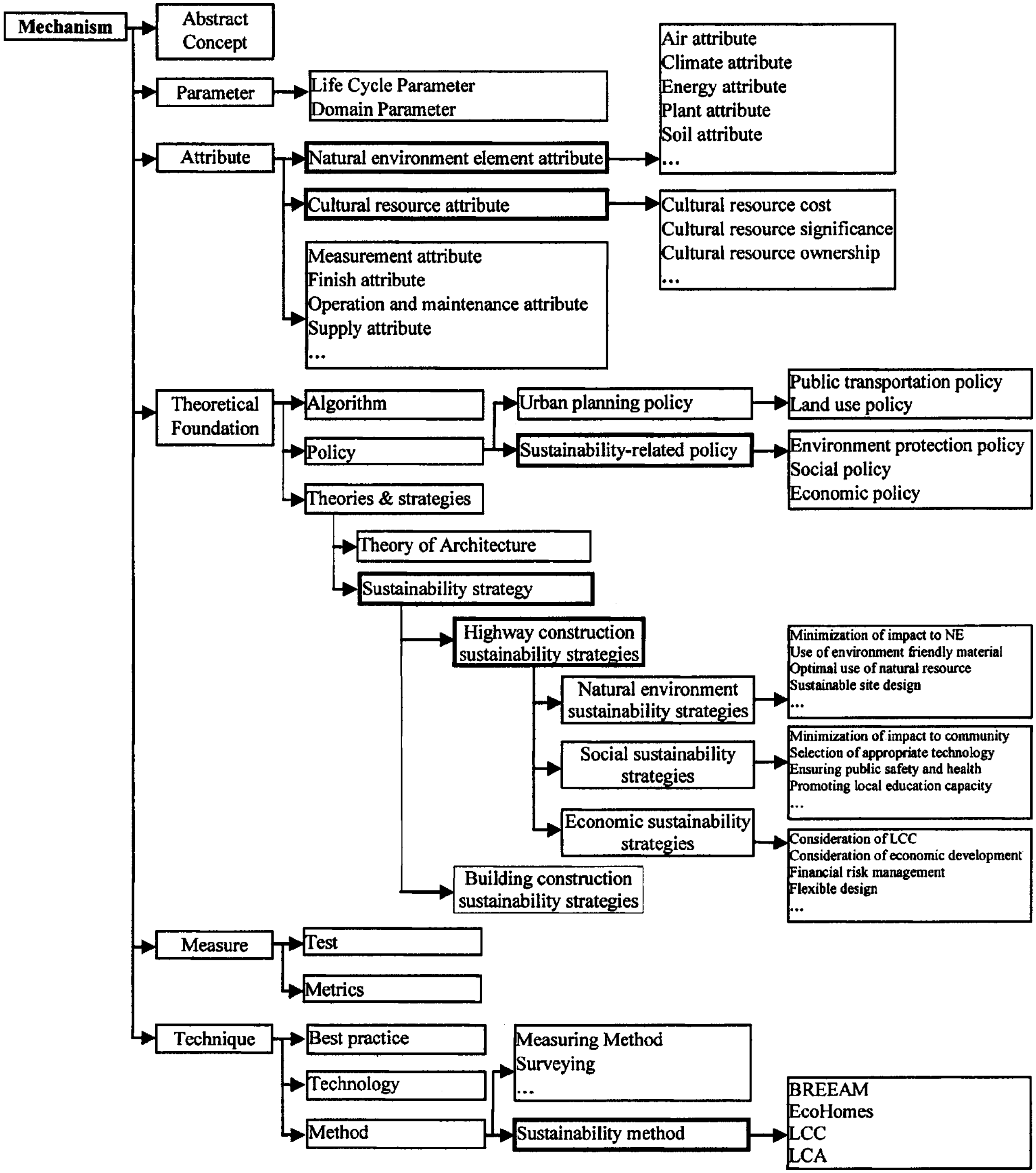

Fig. 4. Overview of mechanisms

- *Attributes*: describes the characteristic of an Entity, such as *Fertility* and *Salinity* of *Soil*.
- *Techniques*: includes *Best practices*, *Methods* and *Technology* used in construction industry.
- *Measures*: includes *Test* (for physical entities) and *Metric* (for logical entities).

To elaborate on one example, let us consider *Highway construction sustainability strategies,* which are categorized under *Sustainability strategies* which in turn is a subclass of *strategies*. *Sustainability strategies* are classified into four categories: *Prevention, Correction, Alleviation*, and *Enhancement strategies*. Prevention strategies focus on predicting the potential impact and risk of the construction project and taking action to avoid these risks beforehand, during its planning and design. Correction strategies emphasize adopting positive measures to rectify any damage to the environment. Alleviation strategies put an emphasis on minimizing already anticipated potential impact & risk. Enhancement strategies aim at enhancing the sustainable performance of a project. At the same time, these strategies are categorized under the three themes: Natural environment, Society, and Economy.

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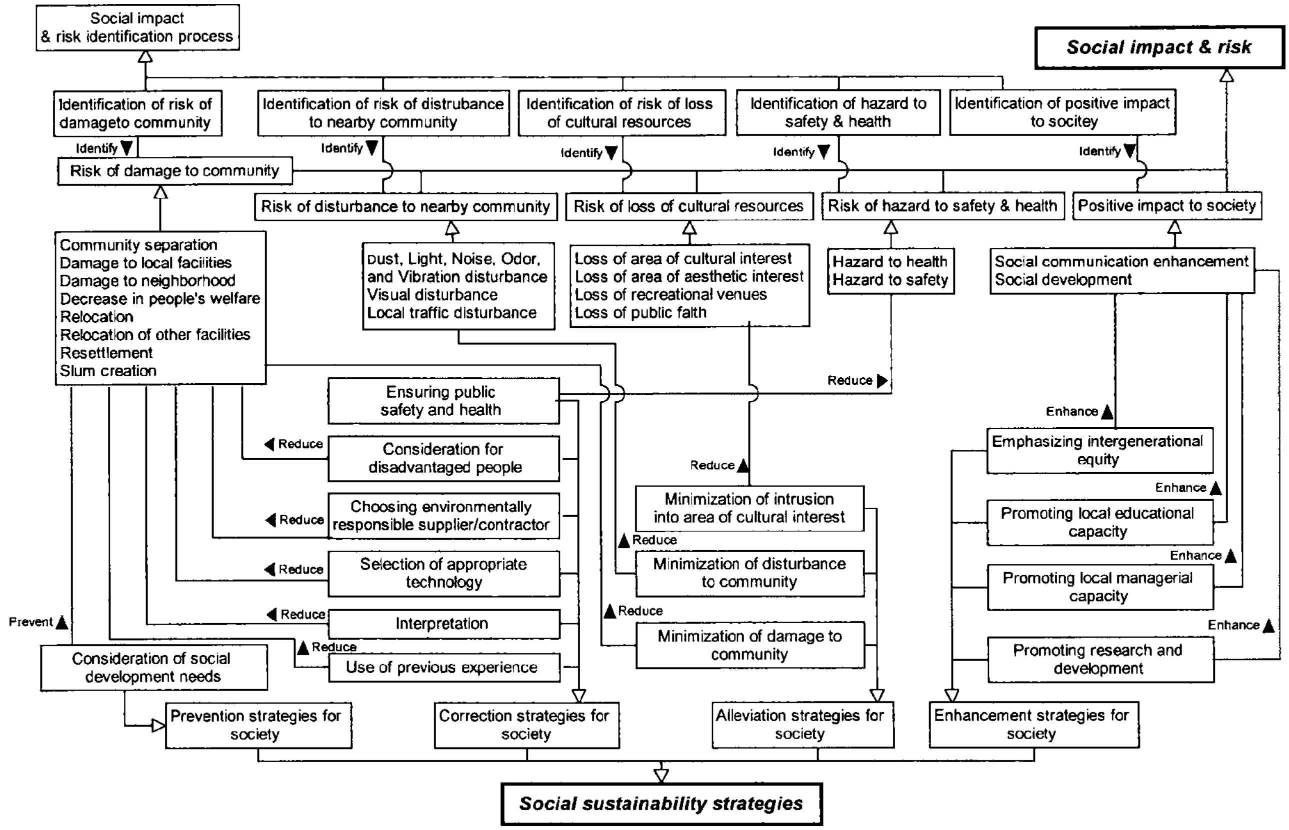

Fig. 5. Social sustainability strategies interrelationship model

Therefore, a similar matrix was constructed with the columns representing the three themes and the rows representing the sustainability strategies.

Constraints

Constraints are defined as the elements that restrict, limit, or regulate various construction entities. *Constraints* is classified into six major groups including *Law*, *Code*, *Specifications*, *User requirements*, *Environmental controls*, and *Social controls*. For example, *Environmental code* includes two major subclasses: *Environment protection code* and *Environmental quality code:*

- *Environmental protection code* is used by environment agencies (Actor) to ensure compliance (Attribute) with environmental regulations. *Environmental protection code* contains Air pollution control code, Land use code, Water resource code, Wildlife protection code, Pesticides code, etc.
- *Environmental quality code* provides a standard for evaluating construction project sustainability, especially in regards to environmental performance (Attributes). Currently, it only consists of two subclasses: *Clear air code* and *Safe drinking water code*.

Technical Topics

This domain is an umbrella for all related domains that have bearing on the construction environment. It encapsulates concepts that pertain to different entities but do not fall under any of the previous domains. *Technical domain* includes 14 first-level subdomains: *Architecture domain*, *Urban planning domain*, *Engineering domain*, *Computer domain*, *Community domain*, *Political domain*, *Economic domain*, *Environmental domain*, *Standards domain*, *Legal domain*, *Safety*, *Management domain*, *Trades and unions domain*, and *Science domain*. S2HOnto focused on *Sustainability domain,* which is a subdomain of *Engineering domain*. For example, it defines:

- *Element related to highway sustainability* includes *Natural environment elements* (e.g., *Basic element of natural environment*, *Natural environment sensitive area*, etc.); *Social elements* (e.g., *Available public facilities*, *Population structure* and *Socially sensitive area*, etc.); and *Economic elements* (e.g., *Employment*, *Income* and *Principle economic activities*, etc.)
- *Highway construction impacts and risks* are the subjects of analysis in many processes and codes. They are grouped into six subclasses: Risk of damage, Risk of loss, Risk of depletion, Risk of pollution, Risk of disturbance, and Positive impact. Another matrix was built to describe the relationships between the three themes of sustainability and this domain:
  - *Natural environment impact and risk* domain comprises *Risk of damage to natural environment* (e.g., *Acid rain*, *Erosion*, etc.), *Risk of disturbance* to *natural environment* (e.g., noise and vibration), *Risk of pollution to natural environment* (e.g., *Air pollution*, *Water pollution*), and *Risk of depletion of natural resources* (e.g., *Depletion of energy*).
  - *Social impact and risk* domain (see Fig. 5) includes *Risk of damage to community* (e.g., *Community separation*, *Loss of area of cultural interest*), *Risk of disturbance to nearby community* (e.g., *Dust disturbance*, *Light disturbance*), *Risk of Hazard to safety and health* (e.g., *Material hazard*, *Waste hazard*), *Risk of loss of cultural resources* (e.g., *Loss of*

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area of aesthetic interest, *Loss of public faith*), and *Positive impact to society*. Fig. 5 shows a subset of the social sustainability optimization process. The figure illustrates the need for defining the types of risks (that should be addressed by these processes), strategies that can be used to address these risks, and a common set of optimization objectives.
- *Economic impact and& risk* covers three major subdomains: *Risk of loss of economic resources*, *Long-term financial risk*, and *Positive impact to regional economy* (e.g., *employment opportunities, growth in economic activity, and enhanced tax revenue*)

Relationships and Axioms

The following represent a sample set of relationships and axioms adopted in the ontology:
- The relationships "participate," "advise _ for," "facilitate," "involved _ in," "perform," and "affect" assign an *actor* to a *process.*
- The relationships "used _ by" and "aid _ in" assign a *resource* to a *process.*
- The relationship "receive" assigns an *actor* to a *product.*
- The relationship "have" assigns an *actor* to a *concern.*
- The relationships "use" and "manage" assign an *actor* to a *resource.*
- The relationship "utilize" assigns a *process* to a *resource.*
- The relationship "defined _ in" assigns a *concern* to a *product.*
- The relationship "support" assigns a *process* to another *process.*

Axioms of the ontology are presented in natural language and First Order Logic. Examples of these axioms are:
- A *stakeholder involvement program* may be *Under _ Development, Under _ Review, Under _ Revision, Approved:*

$$(\forall x)\text{Stakeholder\_Involvement\_Program}(x)$$
$$\supset (\text{Under\_Development}(x)$$
$$\vee\ \text{Under\_Review}(x)$$
$$\vee\ \text{Under\_Revision}(x)$$
$$\vee\ \text{Approved}(x).$$

- An *Approved stakeholder involvement program* requires that the *stakeholder involvement program* is certified by the *Authorized Actor*:

$$(\forall x,y)(\text{Stakeholder\_Involvement\_Program}(x)$$
$$\wedge \text{Actor}(y)\text{Authorized\_To\_Certify\_Program}(y)$$
$$\wedge \text{Certify}(y,x))$$
$$\supset \text{Approved}(x).$$

- p>A *public information dissemination* process has to conform to an *Approved stakeholder involvement program*:

$$(\forall x,y)(\text{Stakeholder\_Involvement\_Program}(x)$$
$$\wedge \text{Approved}(x)$$
$$\wedge \text{Public\_Dissemination\_Process}(y))$$
$$\supset \text{Has\_To\_Conform\_To}(y,x).$$

- A *stakeholder participation* process has to conform to the an *Approved stakeholder involvement program*:

$$(\forall x,y)(\text{Stakeholder\_Involvement\_Program}(x)$$
$$\wedge \text{Approved}(x)$$
$$\wedge \text{Stakeholder\_Participation\_Process}(y))$$
$$\supset \text{Has\_To\_Conform\_To}(y,x).$$

where x,y=variables (ontology objects); $\forall$=for all variables; $\wedge$: logical "and" $\vee$: logical "or"; and $\supset$: results in; yields, equivalent to.

Validation

Ontology validation is, at best, a controversial issue. There is no consistent or agreed-upon standard in this regard (Gómez-Pérez 1996, 2001b). Moreover, given that domain ontologies are not meant to provide universal/exhaustive conceptualization of the knowledge in a domain (they actually aim at providing a "one-of-many" conceptualization), by the virtue of their creation, ontologies challenge our understanding of the subject domain and impose new questions and demand for changes (Boyd 1976). Gómez-Pérez (2001a) suggested the utilization of several techniques based on best practices in knowledge management domain. Three techniques were used to validate S2HOnto: competency questions (CQ), expert surveys, and document search. These were used to address four main validity concerns (Klinker et al. 1990):
1. *Ease of navigation*: it has been found that taxonomies may cause problems, due to their sheer size, related to structuring, retrieval, and maintenance. So it is very important to ensure easy knowledge access, retrieval, reuse, and maintenance.
2. *Abstraction consensus*: there is a need to test if the abstraction used in S2HOnto is valid, i.e., does the ontological model accurately and effectively express the knowledge (tacit and explicit) of the domain.
3. *Representation*: although S2HOnto did not try to exhaustively include all concepts, it is important to test if S2HOnto contains a sufficient number of concepts so that it can adequately represent the domain.
4. *Consistency*: how consistent was the categorization/classification of concepts in the taxonomical trees.

Competency Questions

This technique was championed by Grüninger and Fox (1994) and is widely regarded as one of the most suitable and effective means for ontology validation (Gómez-Pérez 1996; Corcho et al. 2003). Throughout the development of S2HOnto, a set of CQ were used to address concerns 3 and 4. For example, for each product, the following questions represent a sample of the questions that had to be satisfied:
- Who uses the product?
- Which process produces the product?
- What limitations (constraints) apply to the product?
- What varieties (flavors) of the product exist?

Expert Survey

Three experts were involved throughout the various phases of ontology development. Frequent meetings were held with them to solicit their knowledge and assess the effectiveness of our onto-

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Table 1. Response to Question Number 1

Concept	Average
Loss of area of cultural interest	2.4
Energy report	2.9
Minimization of impact to natural environment	2.2
Water pollution	2.7
Economic impact and risk assessment process	2
Damage to community	2.2
Minimization of impact to community	2
Community organization	1.9
Sustainability design software	2.1
Noise assessment report	2.7
Public review process	2.4
Water resource code	2.3
Air	1.8
Natural environnent code enforcement process	2.3
Environment assessment expert	2.3

Table 2. Response to Question Number 2

Concepts	Average
Ozone layer	1.6
Depletion of ozone layer	3.0
Reducing emissions of ozone-depleting substances	2.7
Ozone-depleting substances code	1.6
Ozone depletion assessment report	2.4
End-user	1.0
End-user attribute	4.2
End-user analysis process	2.3
End-user requirements	2.5
End-user analysis report	2.2
Education of sustainability policy	3.3
Sustainability education strategy	2.7
Sustainability educator	1.0
Building for environmental and economic sustainability software	1.2
Loss of public faith	2.6
Professional skill	2.3
Community impact assessment report	1.3
Loss of traditional sense of self-identity	2.0
Land value	2.5
Impact to land value	2.0
Loss of land	2.0
Optimal urban land development strategy	2.5
Land survey process	1.5
Land survey report	1.5
Land use restriction	1.3

logical model and its coverage of the domain. At the end of the ontology development, 12 experts were formally interviewed to test the validity of the ontology.

The survey included seven questions (divided into three sections) that aimed to test the four validity concerns. A six-point scale was used to record the experts' responses, with 1 being the best and 6 being the worst. Below is a summary analysis of the experts' assessment to three of the most important questions:

Section 1: Test the ease of navigation. Experts were asked to locate 15 concepts in the ontology and rate how easy was it to locate them. Table 1 shows the results of their assessment. Generally, experts found it easy (average rating of 2.25) to locate the concepts.

Section 2: Test the effectiveness of abstraction and categorization. Experts were asked to categorize 25 concepts that were intentionally removed from the ontology. The average rating for each concept is shown in Table 2. The overall average was 2.1.

Section 3: overall assessment. This section included five questions:

- Do you agree with the classification of infrastructure sustainability concepts into the eight superclasses: 2.3
- How easy was it to navigate through the taxonomy: 2.6
- How familiar were the concepts used: 2
- How representative are the concepts used: 2.6
- Overall, did the taxonomy cover the main domain of the infrastructure sustainability: 2.3

Test on Sample Document

To test the representatives of the ontology through a different approach, a set of documents related to sustainability were selected to test the representatives of the ontology. This included four steps:

- Extracting concepts: 426 concepts were extracted from the sample documents.
- Classifying concepts based on the skeleton of S2HOnto: the extracted concepts were contrasted/classified under the main classes of S2HOnto.
- Evaluating S2HOnto coverage/inclusion of the extracted concepts: The criteria used to evaluate the covering rate is as follows: if the concepts from the sample document could be found in S2HOnto (either by the same name or by the same meaning), these concepts are said to be fully covered. If the concepts in the sample document do not exist in S2HOnto in terms of the name or the meaning, but similar or related concepts can be identified, these concepts are considered to be partly covered; otherwise, the rest of the concepts are evaluated as not covered.
- Coverage/representatives rate: S2HOnto rates of covering were derived based on assigning a relative weight of 1.0 to fully covered concepts, 0.66 to partly covered concepts, and 0.0 to concepts that are not represented in S2HOnto.

The average match between these concepts and their counterparts in S2HOnto was 84%. Additional sustainability concepts (total of 840 concepts) were also extracted. These concepts relate to sustainability but are not within the domain of S2HOnto. A similar matching procedure was done for the concepts to test how relevant S2HOnto to generic sustainability knowledge. A 25% covering rate was calculated for this case.

Prototype Portal for E-Society

Engaging people in project development is a proven technique to enhance project long-term sustainability and maintainability. There is a need to establish mechanisms to increase community involvement in project planning and decision-making. We need to study the impact and benefits of IT tools and the emerging e-society in coordinating urban renewal, enhancing design sustainability, and reducing impacts on local community (Vincent 1997; Wright 1996). E-society refers to the process of engaging members of the community in identifying strengths and opportunities, problems and potential solutions for infrastructure development schemes. Several initiatives are now being pursued to

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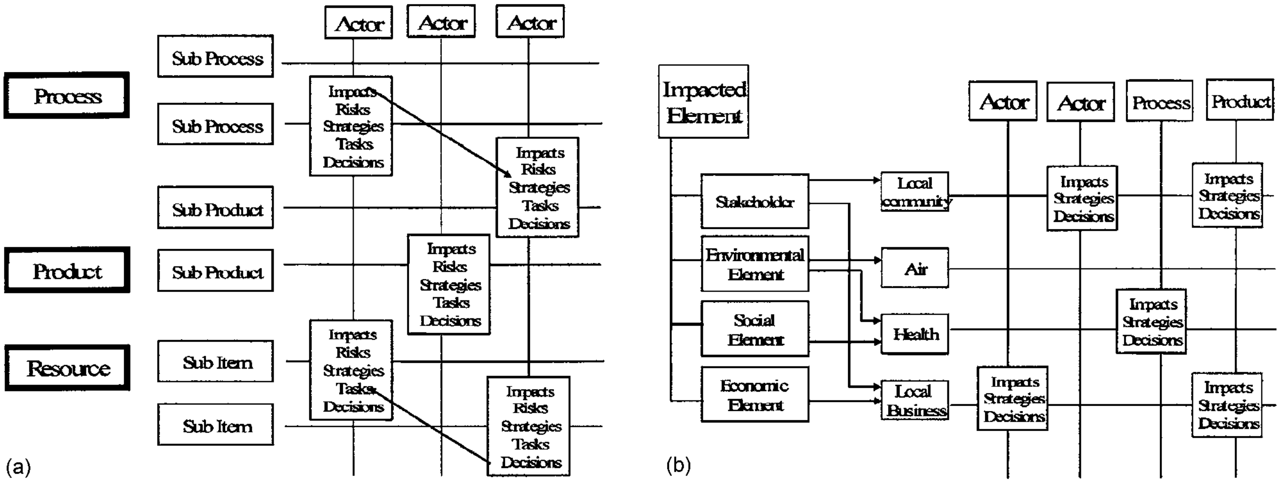

Fig. 6. Functionalities of the e-society portal: (a) entity-decision view (basic view) and (b) impacted element view

involve people in the design process through interactive web (the EU's AUDIENCE project, for example).

S2Honto describes the interrelationships between various sustainability-related entities. Any product (such as a highway, a bridge, a new lane, a parking scheme) is produced through a set of processes, where actors (such as design firms, department of transportation) assume roles in the tasks and decisions for producing/approving products. Each product has a set of impact on various sustainability elements. These elements include, for examples, a stakeholder (such as a business, or a community group), basic environmental elements (such as air, water, and soil). For each of these impacts, a set of strategies could be used to optimize/reduce any negative consequences on the impacted elements. For example, the strategy of *Reducing transportation of material* could be used to reduce pollution to air; other strategies including *Minimization of excavation*, *Minimization of chemical substance erosion*, and *Soil amendment*, could be adopted to avoid/reduce impact to soil; in addition, *Use of recycling water* is one of strategies to reduce negative impact to water.

The research project developed a web-based portal for the exchange of project knowledge related to sustainability and stakeholder management in urban context. The XML-based portal provides several views of the ontology allowing users to navigate project knowledge. For example, Fig. 6(a) shows the basic view that lists all processes and products being developed within a certain project. Along with these, all actors who have decision powers on these processes and products are shown in a matrix format. Each element of this matrix includes subviews that could show the impacts of each actor actions on the sustainability elements and what strategies have been used to mitigate these impacts.

Another matrix could be created to provide different views of the specific project ontology. For example [see Fig. 6(b)], a matrix could be composed of a list of impacted elements and a set of impacts. Elements of the matrix could show which product (option) has caused these impacts, which actor approved such option, or which strategies could be used to alleviate such impacts. Currently, the portal provides the following functionalities:

Customized Project Organization

The ontology provides a default set of relationships between actors and their roles in the development of each product (or the development of major decisions). System administrator can override these by adding new actors, new roles, and new products or new decisions. System administrator can also establish (or override) new relations between actors and their roles in product development and decision making. Such flexible system was needed as no one organizational structure will suit all projects.

Informing Community

A multiperspective map allows all stakeholders to browse all possible design options (for each product) and the impacts of each option on impacted entities. This includes:

1. Project information:

- Present project physical components to the community through a 3D CAD and GIS visualization.
- Present the project organizational structure: who is responsible for which portion of the project.
- Present the main project constraints (including the physical conditions, project objectives, code requirements).

2. Project decisions: Enumerate project major decisions, who made which decision, what are the anticipated impacts of each decision on the sustainable development of local community (for example, impacts on air quality, traffic patterns, noise levels, impacts on local business).

Community Input

The portal provides the following functions:

- Record user profile to support data mining and pattern discovery.
- Document community input regarding design options and anticipated impacts (commenting or voting format).
- Provide data about their future plans (especially business plans) for the design team to include as constraint or elements of the design.
- Allow interested stakeholders to build varying design options and present them as alternatives to the base design

At various points, the system allows any stakeholder to document their concerns regarding a design option, an impact, or a construction method. These comments are organized in a structured manner (through links to ontology concepts) and are stored in a database. Over time, city managers can mine these documents to discover common patterns of community concerns.

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Table 3. Composition of the Validation Group

Number	Organization/position	Experience (years)	Field of experience
1	Consultant	25	Capital management, project planning and provision
2	Academia	7	Environmental engineering, project management
3	Academia	12	Structural engineering, sustainable construction
4	Consultant	6	Urban water system, life cycle costing, stakeholder management.
5	Consultant	8	Water resource, urban sustainability
6	Senior manager, utility company	20	Infrastructure development, stakeholder management, project management
7	Contractor	6	Architectural engineering, project management, project finance
8	NGO	15	Sustainable organizations, stakeholder management
9	Consultant	17	Transportation planning, project finance
10	Senior manager, City of Toronto	14	Stakeholder management, environmental assessment, project development
11	Contractor	21	Telecommunication/electrical infrastructure, environmental assessment
12	Public official	13	Urban planning, project finance

Design Support

A semantic database of best practice and lessons learned provides designers and decision makers with easy access to collective wisdom on the optimization of designs. Unlike hypertext search, semantic search is conducted through navigating documents (in this case lessons learned) using the ontology as a guide.

Conclusions

This paper presented an ontology for stakeholder management and sustainability in highway construction. The ontology categorizes domain concepts into entities (projects, processes, products, actors, and resources), mechanisms, constraints, ontological concepts, basic concepts, and technical topics. Based on reviews of ontology validation best practices, the ontology was validated through the use of competency questions, interviews with industry experts, and testing (comparison) against user documents.

The ontology was used to establish a prototype portal for e-society, where developers of new highway can communicate the impacts of various project options to local community. It provides capabilities similar to the state-of-the-art in traditional web-based project sites. It also allows stakeholders to view who made which decision in the component life cycle, what are the applicable codes, what are the best practices that have been implemented. Finally, it allows stakeholders to vote/comment on the decisions made. It also allows them to post a pdf file of alternative solutions. Educated stakeholders (or professional consultant

Table 4. Ease of Navigation

		Ease of Finding					
		Very Easy	Moderately Easy	Easy	Moderately Difficult	Difficult	Very Difficult
NO.	**Concepts**	**1**	**2**	**3**	**4**	**5**	**6**
1	Loss of area of cultural interest						
2	Energy report						
3	Minimization of impact to natural environment						
4	Water pollution						
5	Economic impact & risk assessment process						
6	Damage to community						
7	Minimization of impact to community						
8	Community organization						
9	Sustainability design software						
10	Noise assessment report						
11	Public review process						
12	Water resource code						
13	Air						
14	Code onformance process						
15	Environment assessment expert						

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Table 5. Classification Effectiveness

NO.	Concepts	Suggested Super Class (Pl. Tick which one is most appropriate): Actor	Process	Resource	Product	Basic Concept	Constraints	Mechanism	Technical Domain	Ease of Classification (Pl. Tick one): Very Easy 1	Moderately Easy 2	Easy 3	Difficult 4	Moderately Difficult 5	Very Difficult 6
1	Ozone layer														
2	Depletion of Ozone layer														
3	Reducing emissions of ozone-depleting substances														
4	Ozone-depleting substances code														
5	Ozone depletion assessment report														
6	End-user														
7	End-user attribute														
8	End-user analysis process														
9	End-user requirements														
10	End-user analysis report														
11	Education of sustainability policy														
12	Sustainability education strategy														
13	Sustainability educator														
14	Building for environmental and economic sustainability (BEES) software														
15	Loss of public faith														

Note: **Very Difficult** means you cannot exactly classify the concept in one of the superclasses and if you classify it in one of the super classes , you feel that it is arguable.

hired by interested stakeholders) can illustrate (through access to the ontology) how the suggested alternative addresses some of the concerns of community (through utilizing some of the already available best practice) or meets code requirements.

Appendix. Validation Interviews

The composition of the validation experts is shown in Table 3. The experts were selected based on three main criteria:

- Extensive knowledge in at least two aspects of sustainable construction/urban engineering. This is reflected in the years of experience as well as experience variety (technical and professional knowledge in design, planning, and construction aspects)
- Be currently involved in the provision of infrastructure project or setting the public policy of infrastructure systems.
- Representation of various public, private and academic entities The following presents a summary of the survey guide

Question 1

The following concepts are classified under different superclasses; using the taxonomy of infrastructure sustainability please indicate how easy it is to locate the concepts (see Table 4).

Definitions of Concepts in Question 1

1. Loss of area of cultural interest—impact/risk which is caused by the physical intrusion of construction and use of infrastructure/building intruding into the area of cultural interest.
2. Energy report—report showing the potential for substantial savings in a typical building or civil products.
3. Minimization of impact to natural environment—strategy to reduce impact which is caused by the physical intrusion of construction and use of building/infrastructure into the natural environment.
4. Water pollution—degradation of a body of water by pollut-

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Table 6. Independent Classification of Concepts

No.	Concepts	Suggested Super Class (Pl. Tick which one is most appropriate): Actor	Process	Resource	Product	Basic Concept	Constraints	Mechanism	Technical Domain	Ease of Classification (Pl. Tick one): Very Easy 1	Moderately Easy 2	Easy 3	Difficult 4	Moderately Difficult 5	Very Difficult 6
1	Professional skill														
2	Community impact assessment report														
3	Loss of traditional sense of self-identity														
4	Land value														
5	Impact to land value														
6	Loss of Land														
7	Optimal urban land development strategy														
8	Land survey process														
9	Land survey report														
10	Land use restriction														

ants in the construction process such as industrial waste water, etc.

5. Economic impact and risk assessment process—process of involving and comparing the costs and benefits of projects throughout their lifetime, incorporating natural and social environmental considerations into a cost-benefit analysis.
6. Damage to community—impact to community due to project construction, operation and maintenance, which includes community separation, damage to local facilities, and damage to neighborhood, etc.
7. Minimization of impact to community—strategy to reduce impact which is caused by physical intrusion of construction and use of building/infrastructure into community.
8. Community organization—organization composed of community people, which deals with certain issues that are of concern to the whole community.
9. Sustainability design software—support tool to assist green design.
10. Noise assessment report—report produced while implementing noise assessment process.
11. Public review process—process of the local community involvement in the project design and formulation from the very start and during the various stages of the project cycle.
12. Water resource code—specified standards to control the potential impact which the project has on water.
13. Air—basic natural environment element which is a mixture of invisible, odorless, and tasteless gases and surrounds the earth's surface.
14. Natural environment code enforcement process—process of being consistent with specific natural environment codes during project development.
15. Environment assessment expert—individual who will be involved in the natural environment sustainability process.

Question 2

The following concepts shown in this table are not currently part of the taxonomy of infrastructure sustainability; please classify them in one of the eight superclasses of this taxonomy (see Table 5).

Definitions of the Concepts in Question 2

1. Ozone layer—basic natural environmental element which acts as a shield to protect the earth from solar radiation.
2. Depletion of ozone—chemical destruction of the ozone layer beyond natural reactions, which could be caused by the emission of ozone-depleting substances during project development.
3. Reducing emissions of ozone-depleting substances—strategy to reduce the emission of ozone-depleting substances. For example, when reusing buildings, inventory existing building systems using refrigerants and fire suppression chemicals and replace those that contain HCFCs or halons; while for new buildings, specify refrigeration and fire suppression systems that use no HCFCs or halons.
4. Ozone-depleting substances code—specified standards to control the emission of ozone-depleting substances during project development.
5. Ozone depletion assessment report—report produced in the ozone depletion assessment process.
6. End-user—individual who will use or operate the infrastructure/building.
7. End-user attribute—characteristic of end-user such as age, gender role and so on.

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Table 7. Ontological Model

Please rate your response on significant scale from 1 to 6	
1	Insignificant
2	Low significance
3	Moderate significance
4	Significant
5	Very significant
6	Major significance

8. End-user analysis process—process of analyzing end-user's attributes requirements and so on.
9. End-user requirement—needs or constraints to the project, which come from the end-user.
10. End-user analysis report—report produced in end-user analysis process.
11. Education of sustainability policy—public policy to help individuals, school systems, and organizations educate for sustainability.
12. Sustainability education strategy—strategy which plays a proactive role in developing education for sustainability and will promote networking and share the best practice in terms of providing support to schools and organizations.
13. Sustainability educator—individual who will be involved in the education for sustainability.
14. Building for environmental and economic sustainability (BEES) software—software used to improve environmental and economic sustainability for building products.
15. Loss of public faith—failure of recognition due to unexpected negative effects or unfulfillment of the expected value of the project.

Question 3

The following concepts were removed from the ontology; please classify them in one of the eight superclasses of this taxonomy, (see Table 6).

Definitions of Concepts above in Question 3

1. Professional's skill—attributes of a professional.
2. Community impact assessment report—output product produced in community impact assessment process.
3. Loss of traditional sense of self-identity—for traditional peoples, their living community is an inextricable part of themselves, their lifestyle, and their livelihood. Hence new infrastructure/building construction may disrupt this sense of identity by opening up areas or resettlement.
4. Land value—the total value of the land, including any upgrades or improvements to the land, which is a kind of regional economic element.
5. Impact to land value—change of land value including increase and decrease which are caused, respectively, by the construction project's benefits and nonbenefits.
6. Loss of land—impact/risk of having owners lose their land due to the construction of projects.
7. Optimal urban land development strategy—strategy to improve optimization of urban land development.

Table 8. Overall Assessment

		Rating scale					
Number	Questions	1	2	3	4	5	6
1	How easy was it to navigate through the taxonomy?						
2	How familiar were the concepts used?						
3	How representative are the concepts used?						
4	Overall, did the taxonomy cover the main domain of the infrastructure sustainability?						

8. Land survey process—process of investigating detailed information of land, especially land use.
9. Land survey report—output product produced in land survey process.
10. Land use restriction—restriction which will control land use.

Question 4

Do you agree with the classification of infrastructure sustainability concepts into the eight superclasses i.e., actor, process, resource, product, basic concept, constraints, mechanism and technical domain? (see Table 7).

Question 5

Is/Are there any other sustainability concept(s) that have not been classified in the superclasses used in the taxonomy? If yes, please name the concept that you think could not be classified in the eight superclasses.

Question 6

Based on your navigation, please answer the following. Rate your comments on 6-point scale (1–6) where 1 is the best and 6 is the worst (see Table 8).

Question 7

If you have further comments/observations you wish to share, please provide your comments/observations in the following comments template.

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