A Framework for Incorporating Sustainability Design Concepts into Performance-Based Engineering in Civil and Environmental Engineering Education

Yue Li and Qiong Zhang

Department of Civil and Environmental Engineering
Sustainable Futures Institute
Michigan Technological University
Houghton, Michigan 49931

Abstract: The objective of sustainability design for human and industrial systems is to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment. Performance-based engineering (PBE) represents a new approach ensuring that a building or other constructed facility achieves the desired performance objectives when subjected to a spectrum of natural or man-made hazards. Even though sustainable design concepts and PBE are still in their early development stages, it is vital to educate students now to better prepare them to face many challenges in professional practice in the 21st Century. However, there is no existing civil and environmental engineering curriculum that addresses both PBE and sustainable design. The objective of this paper is to propose a framework of integrating PBE, viewed by many as the next generation design, and sustainability principles in civil and environmental engineering education The assessment component of evaluating student's understanding of integration of PBE and sustainability design are discussed.

Keywords: Civil and Environmental Engineering Education; Curriculum; Performance-Based Engineering; Sustainability Design.

Introduction

PBE represents a new approach, viewed by many as the next generation design, one that aims at ensuring that a building or other constructed facility achieves the desired performance objectives when subjected to a spectrum of natural or man-made hazards. PBE provides a rational basis for design, with flexibility in accommodating various needs of building occupants, owners and the public, while maintaining the primary objective of safety of human life. The proposals for PBE that have been published in recent years by organizations such as Federate Emergence Management Agency (FEMA), National Earthquake Hazard Reduction Program (NEHRP) and Structural Engineers Association of California (SEAOC), among others, all have common features. All proposals for PBE require that life safety (LS) must be preserved under "severe" events. Beyond this, they stipulate that collapse (collapse prevention, or CP) shall not occur under "extreme" events and that building function (continued function or immediate occupancy - IO) should not be unduly disrupted under “moderate” events. The definitions of what is “severe,” “extreme,” or “moderate” have yet to stabilize, but are likely to be based on the annual probability of exceeding the design hazard or its return period. As an example, one might require that the building be designed so that there is no disruption of function following an event with 50% probability of being exceeded in 50 years (abbreviated in the sequel as a 50%/50-yr event), that life safety is preserved under a 10%/50-yr event, and that collapse will not occur under a 2%/50-yr event. These general performance objectives are encapsulated in a matrix of performance objectives vs. hazard levels for various building occupancies. An illustration of such a matrix is presented in Figure 1 (SEAOC, 1995).

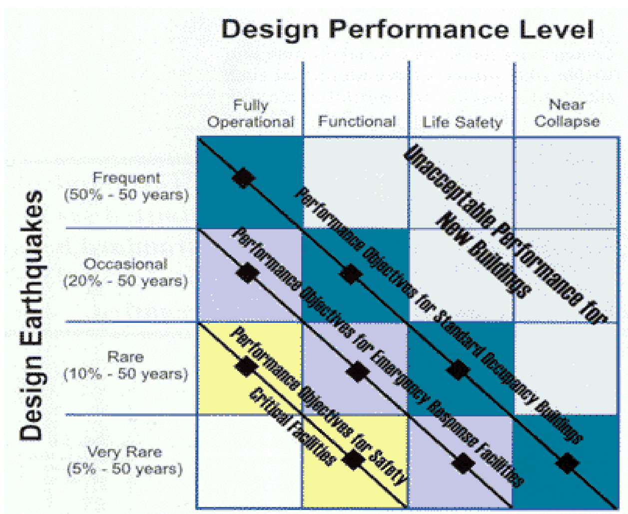

Figure 1 SEAOC VISION 2000 Performance Objectives (SEAOC, 1995)

A fundamental premise of PBE is that performance levels and objectives beyond life safety can be quantified, that performance can be predicted analytically with sufficient confidence, and that risk to the building from uncertain natural hazards can be managed to remain at a level acceptable to the building owner and its occupants. PBE not only can provide tools for assessing risk due to natural hazards such as hurricanes and earthquakes but also promises reliable and predictable performance of engineered construction under a wide range of loadings, which can result in economic protection of property. Due to uncertainties in natural hazard, structural demand and capacity, the performance levels and objectives only make sense if they are probability-based.

Building codes were revised based on the performance-based approach in the United Kingdom, New Zealand, and Australia (Inokuma, 2002). In Japan, the Building Standard Law has changed and is now permitting performance-based design to take advantage of novel technologies such as health monitoring, adaptive systems, intelligent materials, and intelligent systems (Aktan et al. 2007). In the USA, new building codes are updated with performance-based philosophy. In 2000, International Building Code (IBC) 2000 served as a starting point toward performance-based standards for new buildings in the USA. The current IBC 2006 includes four performance groups ranging from “low hazard to humans," to "essential facilities." However, performance-based design has not been explicitly included in Civil and Environmental Engineering (CEE) education so far for CEE programs.

In the meantime, with the growing concerns over population growth, limited resources and environmental impact of human activities, the civil infrastructure system (CIS) has to be designed in a sustainable manner. The objective of sustainability design for human and industrial systems is to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health, and the environment (Mihelcic et al., 2003). Mihelcic and Hokanson (2005) developed a conceptual Sustainable Futures Model (Figure 2), which shows sustainability comprised of the triple bottom line: economic/industrial sustainability, environmental sustainability, and societal sustainability. The model identifies the key components of the three facets and incorporates societal and environmental concepts into engineering education. However, the scientific and technical approaches to designing CIS have not historically focused on long-term sustainability and the concept of sustainability has not been incorporated into the CEE curriculum. A recent survey of the national civil engineering curriculum (Russell et al., 2005) shows that no advance course in sustainability or systems engineering was required in the programs surveyed, and the majority (65.6%) of the programs do not offer a basic course in "CE Systems and Design." There have been growing interests in the role of higher education in achieving sustainability and increasing number of calls for student training in this area. To respond to this challenge to civil engineering education, the American Society of Civil Engineers (ASCE) states that "The Code of Ethics of ASCE requires civil engineers to strive to comply with the principles of **sustainable development** in the performance of their professional duties…" (ASCE, 2001).

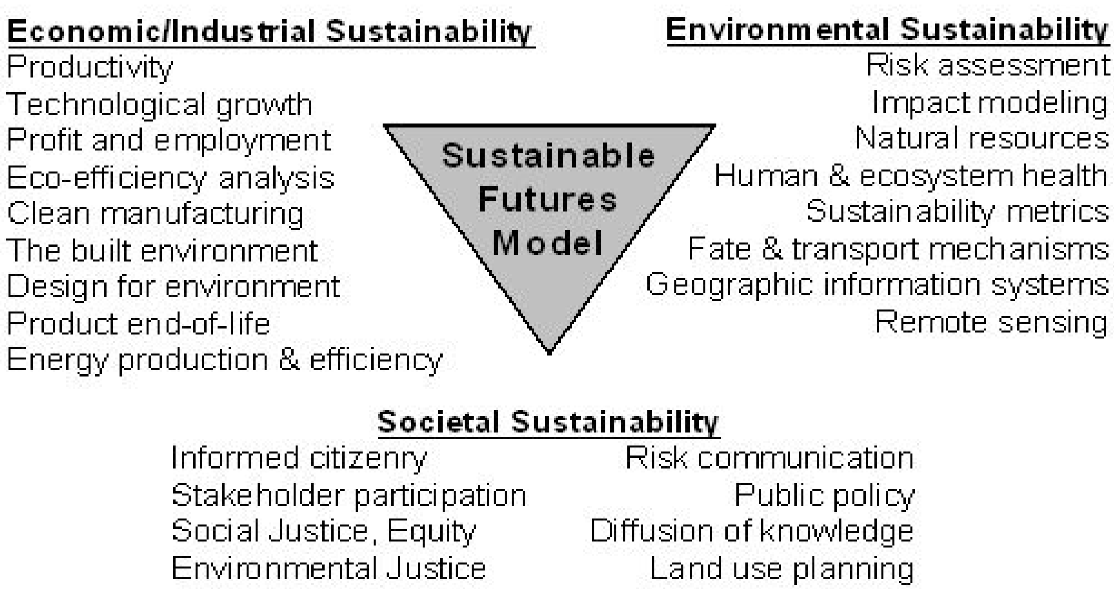

Figure 2. Sustainable Futures Model (from Mihelcic and Hokanson, 2005)

Challenge and Opportunity

Even though PBE and sustainable design concepts are still in their early development stages, it is vital to educate students now to better prepare them to face many challenges in professional practice in the 21st Century. However, there is no existing civil and environmental engineering curriculum that addresses both PBE and sustainable design. It is impossible to design sustainable civil infrastructure while keeping the essential merits of PBE design without an integrating effective training for the students. How to address that is a challenge, but also an opportunity for educators in CEE. It is difficult to add a separate course on sustainability engineering, given the already heavy CEE curriculum in most universities. The integrated curriculum needs sustainability concepts to be introduced in a broad manner. Students will be educated through the existing courses without adding a new specific course on sustainability. PBE, environmental, economic and social aspects of sustainability design need to be considered as a whole in the design process.

In some cases, PBE and sustainable design philosophy are consistent. The design option with the best technical performance based on PBE principles has the maximum economic, environmental and societal benefits based sustainability principles. In other cases, either PBE or sustainable design may control the design. For instance, structural performance may control design when consequences of engineering failure are severe, while sustainable design will play a dominant role when environmental concerns are more important. Reconciling this is another challenge. Table 1 (Akten et al. 2007) summarizes the limit-states, limit-events, and expected performance goals that are being recommended by ASCE on PBE design and evaluation of constructed facilities. Limit states for PBE design need to be described first for performing PBE. Limit states are defined as constructed systems failing to satisfy the prescribed requirements. The four limit states listed in Table 1 are life-cycle utility and sustainability, serviceability and durability, life safety and stability of failure, and substantial safety. These limit states include the concepts of both PBE and sustainability design. That table may serve as a starting point for an integrated curriculum. With that, students are able to weigh the balance of performance-based control and/or sustainability (i.e. environmental or life quality index) control design philosophy.

Table 1. Limit States, Limit Events, and Performance Goals (from Akten et al. 2007)

Limit States	**Utility and Functionality**	**Serviceability and Durability**	**Life Safety and Stability of Failure**	**Substantial Safety at Conditional Limit States**
Limit- events	▪ Environmental impacts ▪ Social impacts ▪ Sustainability of functionality throughout lifecycle ▪ Financing: Initial cost and life-cycle costs	▪ Excessive: Displacements, Deformations, Drifts ▪ Deterioration ▪ Local damage ▪ Vibrations	▪ Excessive movements, settlements, geometry changes ▪ Material failure ▪ Fatigue ▪ Local, Member Stability failure	Lack of: Multiple escape routes in buildings Lack of: Post-failure resiliency leading to Progressive collapse of buildings
	▪ Operational: capacity, safety, efficiency, flexibility, security ▪ Feasibility of: construction, protection, preservation ▪ Aesthetics	**Lack of Durability:** Special limit-state that should govern aspects of global design, detailing, materials and construction	**Stability of Failure:** ▪ Incomplete premature collapse mechanism(s) without adequate deformability and hardening ▪ Undesirable sudden-brittle failure mode(s)	Cascading Failures of Interconnected Infrastructure Systems Failures of Infrastructure Elements Critical for Emergency Response: Medical, Communication, Water, Energy, Transportation, Logistics, Command and Control
Goals	▪ ***Multi-objective performance function for integrated asset-management:*** Functions Relating to Operations and Security	▪ ***Multi-objective performance function for integrated asset-management:*** Functions Relating to Inspection, Maintenance and Lifecycle	▪ ***Multi-hazards risk management:*** Assurance of Life-safety and quick recovery of operations following an event (Days-months)	▪ ***Disaster Response Planning:*** Emergency management, protection of escape routes, evacuation, search and rescue needs, minimize casualties. ▪ Economic Recovery (within Years)

Framework of Integrating Sustainability and PBE

An integrated curriculum for PBE and sustainability is essential to address the issue identified above. The curriculum should provide a breadth of material to equip students with the concepts and means to incorporate sustainability design awareness into PBE. Sustainability and PBE themes should be reflected in the individual courses and in the overall CEE program. The basic components in integrated course design (Fink, 2003) for significant learning include: formulate the learning goals, select the teaching/learning activities, and design the feedback and assessment procedures**.**

Learning Goals

When the principles of integrated design are applied to the framework of integrating sustainability and PBE into CEE curriculum, the following learning goals are formulated: (1) familiarize students with the concept of sustainability and existing methods for sustainability assessment; (2) introduce students to the application of sustainability for solving problems and making decisions; (3) challenge students to find their values and roles in sustainable development; and (4) educate students on the difference between prescriptive and traditional code-based approach that is process-oriented and PBE that is product-oriented.

Teaching/Learning Activities

Course content and teaching/learning activities have to be designed carefully to achieve the above learning goals/pedagogical objectives. First, in the integrated curriculum, the sustainability concept should be introduced in early stage of the curriculum. For instance, Introduction to Probability and Statistic is a required course in many university curriculums. The class is essential to understand performance-based design, which involves various sources of uncertainty. The class should also emphasize the probabilistic aspect of society and environmental impact. When construction material class is taught, material selection should be considered from both structural performance and sustainable built material perspectives.

Second, design courses and capstone projects provide an opportunity for students to apply what they learn in classrooms about PBE and sustainability to “real world” examples. Working on projects will test whether students are able to understand the initiatives and principle of PBE and sustainable design. Many design courses including steel, concrete, wood structure and bridge design are moving toward PBE design to make sure structural performance is acceptable under a spectrum of natural and man-made hazards. In addition, energy-efficient, environmentally friendly themes in a life cycle perspective should be reflected in such design. Primary measurable factors contributed to sustainable design include site selection, energy consumption, materials, and emissions. How these factors may influence the performance of building and transportation system should be considered when performing (or incorporating) PBE.

Third, knowledge of green engineering principles, life-cycle concept, societal impact, environmental impact and resource consumption can be included as separate modules in existing classes. The flexibility and independency of these modules will ensure the majority of CEE programs are influenced. For example, three modules can be developed on sustainability design: (1) introducing sustainability which includes definition of sustainability (triple-bottom-line), evolution from pollution control to sustainability, existing method for sustainability assessment (life cycle impact assessment, life cycle costing, social and policy analysis); (2) evaluating material flow which includes life cycle material inventory, source reduction options, recycling options and technologies, and sustainability-oriented material selection; and (3) evaluating energy flow which includes life cycle energy inventory, energy resource options (renewable or non-renewable), impacts of energy consumption, and energy saving technologies. With this knowledge, students will be able to understand the impact of engineering solutions in a societal and environmental context. Table 2 illustrates how to include the sustainability modules, along with other dependent class content ingredients, into class content to achieve the learning goals through various teaching/learning activities.

Table 2. Incorporating Sustainability Modules into Class Content

Learning Goals	Content	Activities
Goal 1 - Familiarize students with the concept of sustainability and existing methods for sustainability assessment	Module 1 – Introduction to Sustainability: definition of sustainability (triple-bottom-line), evolution from pollution control to sustainability, existing method for sustainability assessment (life cycle impact assessment, life cycle costing, social and policy analysis)	Lecture Demonstration of life cycle assessment software
Goal 2 - Introduce students to the application of sustainability for solving problems and making decisions	Module 2 – Material flow: life cycle material inventory, source reduction options, recycling options and technologies, and sustainability-oriented material selection	Lecture
	Case study: material selection	Group project
	Module 3 – Energy flow: life cycle energy inventory, energy resource options (renewable or non-renewable), impacts of energy consumption, and	Lecture

	energy saving technologies	
	Case study: energy conservation	Group project
Goal 3 - Challenge students to find their values and roles in sustainable development	Sustainable solutions of case study and the role of engineers	Student presentation
Goal 4 - Educate students on the difference between prescriptive and traditional code-based approach that is process-oriented and PBE that is product-oriented	Difference in design philosophy, design procedure, expected structural performance, and construction cost associated with code-based design and performance based design	Lecture Group project of design course Capstone project

Lastly, to meet the need of interdisciplinary nature of such integration, the curriculum should require students to take some courses (e.g. 9 credits) from other disciplines. For example, civil engineering students may need to take courses on green engineering, life cycle engineering, sustainability assessment methods/tools, natural resource and environmental economics, energy economics, natural resource policy, energy technology and policy, human dimensions of natural resources, risk communication, and sociology of the environment.

Feedback and Assessment Procedures

The feedback and assessment components of the integrated curriculum are to evaluate the effectiveness of students' understanding of integration of PBE and sustainability. The assessment includes student self-assessment, peer review, and employer surveys (Chau, 2007).

Student self-assessment may take the form of exit-interview conducted when students graduate. The self-assessment will ask specific questions regarding sustainability engineering and PBE. The questions may include: Do you believe that your education was broad enough to allow you to understand the concepts of sustainability design in a PBE context. What would you like to be included in your education that can enhance your understanding and application of sustainability concepts in engineering design?

Peer review is for project team members to evaluate other teams and other individuals within the same team. Effectiveness of incorporating sustainability awareness and performance-based design philosophy into their project will be evaluated. The peer review will account for part of the total grade of the team project.

While student self-assessment and peer review offer opportunities for students to examine their awareness on applying sustainability concepts to the next generation of engineering design, employer surveys provide feedback on how well the graduates apply the principles of sustainable and PBE to their work.

Summary

This paper identifies the pressing need of incorporating sustainability design concepts and PBE into the CEE curriculum, which is vital to educate students and better prepare them to face many challenges in professional practice in the 21st Century. A framework is proposed on integrating PBE and sustainability principles in CEE education. Learning goals, and teaching/learning activities, and feedback and assessment procedures of such integrated curriculum are discussed.

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