COSTING SUSTAINABLE CAPITAL PROJECTS: A SOCIO-ENVIRO-TECHNICAL PERSPECTIVE

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ABSTRACT

Despite increased motivation to improve the sustainability of capital projects in the United States and beyond, perceptions of their cost, especially first cost, remain a significant barrier. How can the cost of sustainable facilities accurately be predicted during early planning stages when critical go-no go decisions are being made? Total Cost of Ownership (TCO) can be applied at the earliest stages of concept development using an agent-based modeling (ABM) approach to capture both the social and engineering systems that characterize a facility's lifecycle. ABM permits evaluating the impact of the institutional and industry environment on facility design and lifecycle performance while also capturing the cost impacts of tightly coupled facility systems that characterize green design. The ability to simulate TCO for multiple individual facility scenarios provides a basis to decide how best to allocate scarce additional resources among all projects in a portfolio while enhancing sustainability in a way that ensures ongoing organizational functionality and support.

1 INTRODUCTION: SUSTAINABILITY AND BUILT ENVIRONMENT SYSTEMS

As impacts of humans on the environment at both local and global scales become increasingly apparent, sustainability and sustainable development have emerged as goals for human activity toward which all actions should aspire to ensure the ongoing survival and prosperity of the human species (e.g., MDG 2000; OECD 2001; UNCED 1992; WCED 1987). Sustainability implies the ability of a system to maintain itself or be maintained over time without threatening the stability of other systems upon which it depends. However, human-designed systems often exhibit complexity and emergent behaviors that make their sustainability difficult to evaluate. The built environment, including human made structures and infrastructure that provide the foundation for human activities, is one example of this kind of complex system. The objective of this paper is to present a new approach to operationalizing sustainability for the capital facilities that comprise the built environment, and to describe efforts currently underway to implement that approach using Agent-Based Modeling (ABM).

1.1 Built Environment Sustainability

The built environment is an essential component of human activity and a subject of increasing interest for sustainability research and practice. One reason for this is the increasingly undeniable effects of the built environment on natural systems. Major environmental impacts exacerbated by construction activities include climate change, ozone depletion, soil erosion, desertification, acidification, loss of biodiversity, land pollution, water pollution, air pollution, depletion of fisheries, and consumption of resources such as fossil fuels, minerals, and gravel (Hill and Bowen 1997; Kibert 2008; Roodman and Lenssen 1995; Shah 2006). Specifically, in the United States, the building sector annually consumes about 74% of electricity; 39% of primary energy; 19% of natural gas; 6% percent of petroleum; 14% of potable water; 25% of virgin wood; and 40% of raw stone, gravel, and sand; for a total of 3 billion tons of raw materials (EIA 2009; Roodman and Lenssen 1995; USDOE 2008a). In addition, the building sector also accounts for 30% of waste output (136 million tons annually), 38% of all carbon dioxide emissions; and 30-35 million tons of construction, renovation, and demolition (C&D) waste (OECD 2003; USDOE 2008a).

In addition to the impacts of the built environment on the natural environment, built facilities also have a considerable impact on the humans who occupy and use them for various purposes. Indoor aspects of buildings such as air quality, lighting, acoustics, and thermal comfort are strongly related to occupant health, comfort, and productivity (Kats 2003a; Lechner 2009). Evaluating the exact financial impact of healthier, more comfortable facilities is difficult, but the potential magnitude of financial benefit greatly exceeds the capital costs of improving the indoor environment (Romm and Browning 1995). The cost of poor indoor environmental and air quality – including higher absenteeism and increased respiratory ailments, allergies and asthma – are hard to measure and have generally been “hidden” in sick days, lower productivity, unemployment insurance and medical costs (Kats 2003a). According to Fisk et al. (Fisk 2000; Fisk and Rosenfeld 1997) and Kats (2003a), potential U.S. annual savings or productivity gain from improvements in indoor environments are in the range of $43 billion to $236 billion annually.

Thus, both inside and outside built facilities, opportunities abound for change to improve environmental quality and building performance while creating better habitat for humans. These changes fall under the rubric of sustainable construction, defined as construction that meets the needs of present stakeholders while not compromising the ability of non-stakeholders or future humans to meet their own needs (adapted from WCED 1987). Implementing sustainability-related practices and technologies in the construction industry yields many potential environmental, economic, and social benefits such as improving air and water quality, conserving natural resources, reducing operating costs, increasing occupant productivity and satisfaction, and others (Ahn and Pearce 2007, 2009; Kibert 1994; 2005; 2008; Shah 2006; USGBC 2007; 2009a). To achieve these potential benefits, the construction industry has implemented many strategies and technologies for green building design, construction, building operation and maintenance, and even demolition (Kibert 2008; Prowler 2008; Shah 2006; USGBC 2007).

1.2 Modeling and Measuring Sustainability: The Challenges

The concept of sustainability is necessarily complex in terms of modeling or measurement. At the foundation of the problem is the lack of a widely accepted operational definition of the construct of sustainability with respect to technological systems, although efforts to develop such a definition do exist in the literature (e.g., Pearce and Vanegas 2001). In its most literal sense, sustainability is a system state marked by stability, where changes to the system are constrained to ensure that stability into the foreseeable future (Pearce 1999). This system state depends not only on conditions within the system itself, but also on the context in which the system operates, i.e., the larger system(s) of which the system is a part, and the evolving dependencies between them (DuBose 1994; Pearce 1999; Pearce and Vanegas 2001). Accordingly, measuring sustainability has traditionally posed a challenge to those who would use the concept as an objective for decision making. According to the systems-based definition of sustainability, measuring the state of sustainability of a given system requires knowledge not only of the behavior of the elements of the system itself, but also the ripple effects of the system due to its inputs from and outputs to the global Earth system.

Rather than making a global account of all effects of a facility system, conventional approaches to measuring sustainability have typically relied upon indicators commonly believed to reflect system sustainability. For example, the Leadership in Energy and Environmental Design (LEED) green building rating system is based on multiple categories of indicators that survived the rigor of a consensus process

(USGBC 2007). These indicators are not purported to be comprehensive or collectively exhaustive, but they do reflect critical system behaviors such as energy consumption, ecosystem disturbance, and waste generation that influence the sustainability of a built system. At the level of civil infrastructure systems, efforts to date have focused on defining categories of frameworks to represent sustainability of infrastructure systems (e.g., Jeon & Amekudzi 2005) and identifying relevant indicators and appropriate amalgamation methods (e.g., Ugwu et al. 2005a, b).

While indicator-based approaches to sustainability measurement have proven useful in many contexts, they suffer from two basic limitations. First, the outcome of a given tool is dependent upon the selection of indicators. The rationale for indicator selection may not be any more rigorous than the opinions of the tool developers, which differ significantly as evidenced by the variability of indicator categories from tool to tool. Second, indicators are usually incommensurable, i.e., their values cannot be directly combined to form a composite indicator of the sustainability of a facility, meaning that additional means for examining tradeoffs are necessary in order to use to the tools to support decision making. For example, values for thermal comfort cannot validly be added to values for water economy – the units of each indicator are different. Existing evaluation tools do not typically provide any method for normalizing indicators to permit direct comparison of different facilities or different states of the same facility.

Existing rating systems have attempted to overcome the incommensurability challenge using generic points or credits that reflect the relative sustainability importance of each indicator (USGBC 2009, Pearce 2009), but the coarse resolution of these systems provide relatively little guidance to a decision maker seeking to prioritize courses of action to increase facility sustainability, particularly at the early planning stages of projects when facility details are not yet defined. Quantification of tradeoffs among different courses of action is linked to choices of best practices, not necessarily the *outcome* of those best practices in the context of specific facilities. More recent iterations of the LEED rating system have become more performance-based rather than prescriptive, but measured performance after buildings are constructed is often worse than performance of buildings *without* green goals (Hinge et al. 2006; Nelms et al. 2007; Newsham et al. 2008; Torcellini et al. 2004; Turner 2006; Turner and Frankel 2008).

More importantly, existing indicator-based approaches to sustainability evaluation have yet to be embedded effectively within the process of decision making for built facilities. The LEED system, for example, is typically used as a means for establishing a rating for a given facility rather than as a tool for maximizing sustainability over the facility life cycle. It does not incorporate other typical constraints and considerations such as cost or availability of resources within the context of a specific facility that are critical for meaningful decision making.

To overcome these problems, a way of measuring sustainability for built facilities is needed that can be embedded within existing processes for capital facilities planning and resource allocation. Ideally, the approach should also be able to provide information to address observed implementation barriers that are slowing adoption of sustainability in practice.

2 COST-BASED SUSTAINABILITY MEASUREMENT

An approach that *can* be embedded within conventional decision processes is to base sustainability evaluation on cost. To the extent that costs over the life cycle of a facility reflect demands for resources, life cycle costs are a proxy for external resource demand and thus correlate inversely with system sustainability. From a practical standpoint, facility costs also represent a feasibility criterion for a project in terms of an organization's ability to afford those costs over time as they occur. Other sustainability-related externalities such as damage to natural ecosystems can also be accounted for using a cost metric if desired (e.g., Bennett & James 1998). Assuming that all direct and indirect costs and externalities are taken into account, the sustainability of a project should be inversely proportional to its total ownership costs over the life cycle. To the extent that revenues are also taken into account, metrics such as net present value are also a measure of the facility's impact on an organization's financial success. Cost-based measurement of sustainability also offers the opportunity to address one of the most severe barriers to sustainability implementation – the first cost barrier – as described in the following subsections.

2.1 Total Cost of Ownership

Total cost of ownership (TCO) is a major economic metric of managerial and investment strategies, including sustainability initiatives, for capital projects in a portfolio context. Often considered to be equivalent to the lifecycle cost (LCC) of a facility, TCO incorporates considerations of occupancy costs for facilities in addition to hard capital costs. The International Facilities Management Association (IFMA) characterizes TCO as a dollar per square foot value for facilities that includes all facilities-specific costs associated with construction, preservation, maintenance, and operation of the facility, as follows (IFMA et al. 2008):

> *TCO…includes the representation of the sum total of the present value of all direct, indirect, recurring and non-recurring costs incurred or estimated to be incurred in the design, development, production, operation, maintenance of a facility/structure/asset over its anticipated lifespan. (Inclusive of site/utilities, new construction, deferred maintenance, preventive/routine maintenance, renovation, compliance, capital renewal, and occupancy costs.)*

Current approaches to calculating TCO or life cycle costs differ widely based on the type of decision making being supported by the calculation (Asiedu & Gu 1998). At the project scale, TCO is most often used as a metric for comparing project alternatives as part of planning or design (e.g., ibid.; Keys 1990), identifying cost drivers for design changes and optimization (Asiedu & Gu 1998), or as a screening criterion for project funding (Arditi & Messiha 1996). A variety of "bottom up" models exist to estimate lifecycle costs at this scale, when project-specific details are known to some degree (e.g., Asiedu & Gu 1998, Zayed et al. 2002).

At the portfolio scale, TCO is a useful metric for prioritizing facilities for repair or replacement in combination with other metrics such as safety, condition, utilization, or mission criticality – it helps to determine which facilities are costing the most to deliver the required function and what benchmark TCO is possible given other facilities in the portfolio (e.g., Liu & Frangopol 2005). With an increase in portfolio-based management by public sector owners, decision makers would like to be able to accurately calculate what is the true TCO for each facility comprising the portfolio. Estimates of LCC or TCO may be required as part of funding requests for new facilities (e.g., State of Georgia 2007; NAVFAC 2007), but existing facilities often do not yield the necessary data to calculate TCO on an individual facilities scale.

2.2 Cost Uncertainty over the Project Life Cycle

When project details have *not* yet been developed, metrics such as TCO or even detailed estimates of project first costs are more difficult to develop with any certainty. Figure 1 shows an adapted version of the so-called "cone of uncertainty" (Boehm 1981). The cone is typically used with reference to estimating initial project costs in multiple fields, including both construction and software development. It reflects the fact that as additional definition occurs for a project, uncertainty about its eventual cost decreases. The true cost of a project can only be determined for certain when the project is complete.

From a TCO standpoint, the cone also applies in reverse to future operational, maintenance, rehabilitation, retrofit, and eventual disposal costs of the facility. The immediate operational costs are known with greatest certainty at the beginning of the facility's service life, but are known with less certainty over time as components within the facility degrade at various rates and are maintained with varying degrees of rigor. Uncertainty with regard to changing utility costs also contributes to this effect, with risk of increased costs growing greater the farther into the future the projection goes. With the long life cycles typical of built facilities and infrastructure systems, typically 50 years or greater, future changes in use and expectations for building services are also very common, and the interactions of users over time will change accordingly, also affecting future operating and performance costs.

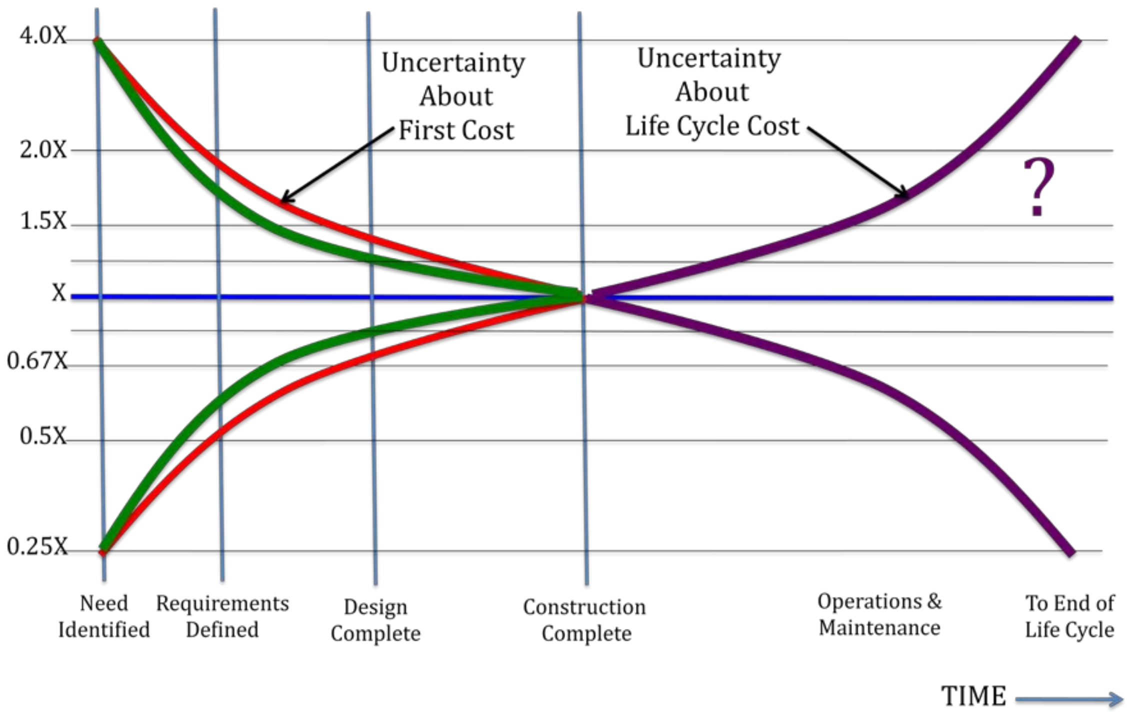

Figure 1: Levels of Uncertainty over Time for Total Cost of Ownership (adapted from Boehm 1981)

How to best predict the cost of a facility before it has been designed? As the level of definition of a project increases, the uncertainty regarding its cost tends to decrease, often exponentially, as key decisions are made and choices locked in. Nevertheless, the ability to make reasonable and accurate estimates before such details are known is critical to the success of a project. Given that the decision to pursue a project or not may depend on the initial cost estimate, developing reliable cost estimates before investing in project design and development is essential.

Conventionally, conceptual estimates for projects at the planning stage are based on historical data from similar projects. However, these estimates may not apply well to innovative projects substantially different from the historical projects on which the data is based, and the set cost of data on green projects remains comparatively small. How, then, to accurately develop early-stage estimates of innovative green projects?

2.3 Status Quo Approaches to Cost Estimating for Green Capital Projects

Green projects are characterized by several unique qualities, including tightly coupled designs and multi-function materials and systems (Riley et al. 2004; Rohracher 2001), procurement of unusual products with limited sources (Klotz et al. 2007a; Pulaski et al. 2003; Syphers et al. 2003), existence of incentives and resources not available to other projects (Grosskopf & Kibert 2006; Pearce 2008; Rohracher 2001), requirements for additional information and documentation (Lapinski et al. 2005, 2006; Pulaski et al. 2003), and greater involvement of later stakeholders in earlier project phases along with greater integration of their input (Cole 2000; Gil et al. 2000a; Matthews et al. 1996; Pulaski & Horman 2005c; Pulaski et al. 2006; Reed & Gordon 2000; Rohracher 2001). While some research has been done to quantify the incremental costs for project design (Larsson & Clark 2000; Enermodal Engineering 2006), incremental costs associated with changes to construction practice remain unexplored, and some authors assert that construction practice remains largely the same despite changes in project requirements (Dewick & Miozzo 2004; Matar et al. 2008).

Tightly coupled integrated design of systems in green projects means that investment in better performing and more expensive systems of one type can result in savings in other systems, often substantially offsetting any additional cost associated with the more expensive systems as well as resulting in lifecycle savings (e.g., Hawken et al. 1999; Kats 2004; Mogge 2004; Pearce 2008). The effects of integrated design are difficult to generalize from case to case and challenging to incorporate in preliminary or conceptual estimates for projects where design details are not developed to any degree, as is the case in public sector projects when initial funding requests are being made. Additional public sector institutional practices such as value engineering have the potential to "undo" some of these tight couplings, further impacting not only the initial project budget but also having the potential to create longer term problems and cost impacts if the building no longer performs as designed. Constraints on system types and sources imposed by public sector procurement requirements impose additional challenges that must be considered when evaluating the potential for integrated design in public sector projects, along with the cost impacts it may have. Common practice for estimating sustainable project costs at the conceptual phase is to add a margin to the estimate for a traditional project to cover anticipated increases in design costs, material costs, and other project costs (Mogge 2004; NAVFAC 2008). This approach has the potential to inhibit the implementation of sustainability for several reasons (Pearce 2008). First, capital projects are typically funded based on efficiency of first cost, meaning that projects with a higher parametric cost estimate are less likely to get funded. Secondly, adding a premium to the project estimate means that even if the project is funded, there is reduced incentive to seek cost savings since the money will be lost if it is not spent, thereby creating a self-fulfilling prophecy of increased costs for sustainable projects.

Beyond first cost, multiple applications have been built to model the lifecycle costs of buildings (e.g., Gustafsson & Karlsson 1987; Fuller & Peterson 1995), infrastructure systems (e.g., Ravirala & Grivas 1995), and construction systems, materials, and assemblies (e.g., Ehlen 1997; Arpke & Hutzler 2005; Migliaccio et al. 2006). Some of these models go beyond the traditional deterministic approach to include explicit consideration of uncertainty (e.g., Zayed et al. 2002, Ravirala & Grivas 1995), risk tolerance of decision makers (e.g., Goda & Hong 2006; Salem et al. 2003), and other social factors that make the outcomes more reflective of the aims of decision-making in practice. However, several recent studies in the building sector have led to concerns about the accuracy of building performance models with regard to forecasting future building energy demands for green buildings, which constitute a significant portion of a building's life cycle costs (e.g., Hinge et al. 2006; Nelms et al. 2007; Newsham et al. 2008; Torcellini et al. 2004; Turner 2006; Turner and Frankel 2008).

In summary, current approaches to estimating cost of green projects are lacking in a number of ways. First, current methods for estimating the first cost of green projects early in the project life cycle contain built-in assumptions that create an artificial cost margin for green projects, leading to a self-fulfilling prophecy that green projects necessarily cost more than conventional projects. Secondly, life cycle cost estimates are dependent upon building performance models that may poorly represent the actual operating costs of green projects. Finally, the comparatively small pool of cost data on green projects provides a relatively weak basis for statistical or parametric approaches to costing green projects. In short, a new approach is needed that takes into account the actual differences between green and conventional projects rather than just using a delta with respect to cost data for conventional projects. That approach should (1) be able to account for interactions among humans, context, and technology that comprise green buildings; (2) be usable at the very earliest stages of design before details about the project are well known; and (3) should take into account the full set of costs associated with ownership of a facility to enable balanced allocation of resources across portfolios of facilities rather than sub-optimizing performance of a single project.

3 MODELING TCO OF CAPITAL FACILITIES

Total Cost of Ownership is an emergent property of systems at both the project and portfolio scales. At the scale of individual public sector projects, TCO is influenced by a number of factors beginning in the planning and design phases, extending through construction, and continuing through operations, maintenance, and the ultimate end of the lifecycle for a facility, including:

- Individual decisions made by a number of decision makers, including members of the design team, owner team, construction team, etc., based on a variety of factors both technical and people-oriented (Pearce 2003; Pearce 2004; Pearce & Fischer 2001a, b). The selection of parties to participate in a capital project is also non-deterministic and influenced by a variety of factors (Keysar & Pearce 2007; Pearce et al. 2005b).
- Influence of procurement constraints such as “Buy American”, minority-owned or small business set-asides, or metrification (Pearce & Fischer 2001b; Pearce et al. 2005a; DuBose et al. 2007).
- Initial program of requirements for the facility, which is necessarily different for each project and which is also influenced by contextual factors describing the environmental, sociopolitical, and organizational context in which the facility will exist and operate (Pearce et al. 2007).
- Quality of construction and degree to which it meets original design intent (Maxey 2006; Newton & Christian 2006).
- Interactions between the facility and its occupants over the lifecycle, both in a formal sense of organizational mission requirements and in an informal sense, where users adapt, enhance, or disable technologies and systems within the facility to adjust it to their needs (e.g., Arpke & Hutzler 2005).
- Changes in demands placed on the facility as the needs and expectations of occupant organizations change over time.
- Availability of new technologies that can be retrofitted or applied to the facility over its lifecycle, resulting in new cost profiles that are different from those assumed during initial design and construction.

3.1 The Role of Stakeholders as Agents in TCO

Figure 2 illustrates the complexity of relationships among stakeholders involved in realizing a facility up to the point of occupancy. Distinct organizations involved with a given project during conventional project delivery include the Owner Team (OT), the Design Team (DT), and the Construct Team (CT). The relationships among these teams include selection of design and construct teams by the owner on the basis of criteria including firm capabilities, capacity to perform the work, work history with the owner organization, and specific procurement restrictions such as minority business set-asides. Additionally, qualified construct teams may also be selected on the basis of criteria such as low bid or best value (Pearce 2003; 2008). Whether or not a given team is selected is also a function of market conditions and whether that team puts itself “on the market” for a given project given its capacity and load in terms of other projects.

Selection of the project team influences the first cost of a project, since the unique design developed and implemented for a specific project is influenced by the history and experience each firm brings to the project. For instance, design teams tend to favor proven technologies over unproven ones (Nam & Tatum 1992), which is a function of both their knowledge of the field and their own history with technologies on past projects. Owner and Construct organizations also favor technologies and practices that have been successfully demonstrated on peer projects, either within their own portfolios or within the portfolios of similar owners (Pearce 2003; Pearce et al. 2005c; Rogers 2003; Toole 1998; Koebel 1999; Koebel et al. 2003; Koebel et al. 2004).

The ultimate facility design (and subsequent as-built performance) of a facility is determined by both system selection and specification by the Design Team, and methods selection and implementation by the Construct Team. These decisions are influenced as well by the history, knowledge, and social networks of the involved team members, the capabilities and capacity of team members’ firms, and specific constraints/objectives imposed by the Owner Team. The result of these decisions is a facility with a Total Installed Cost (TIC) that then goes on to occupancy/beneficial use throughout the rest of its lifecycle with similar or even greater cost-determining complexity. The nature of this facility at the point of turnover to the Owner greatly influences performance and costs for the rest of the lifecycle (e.g., Newton & Christian 2006; Junnila & Horvath 2003; Junilla et al. 2006), as do subsequent use patterns, functional requirements, and competing agency priorities.

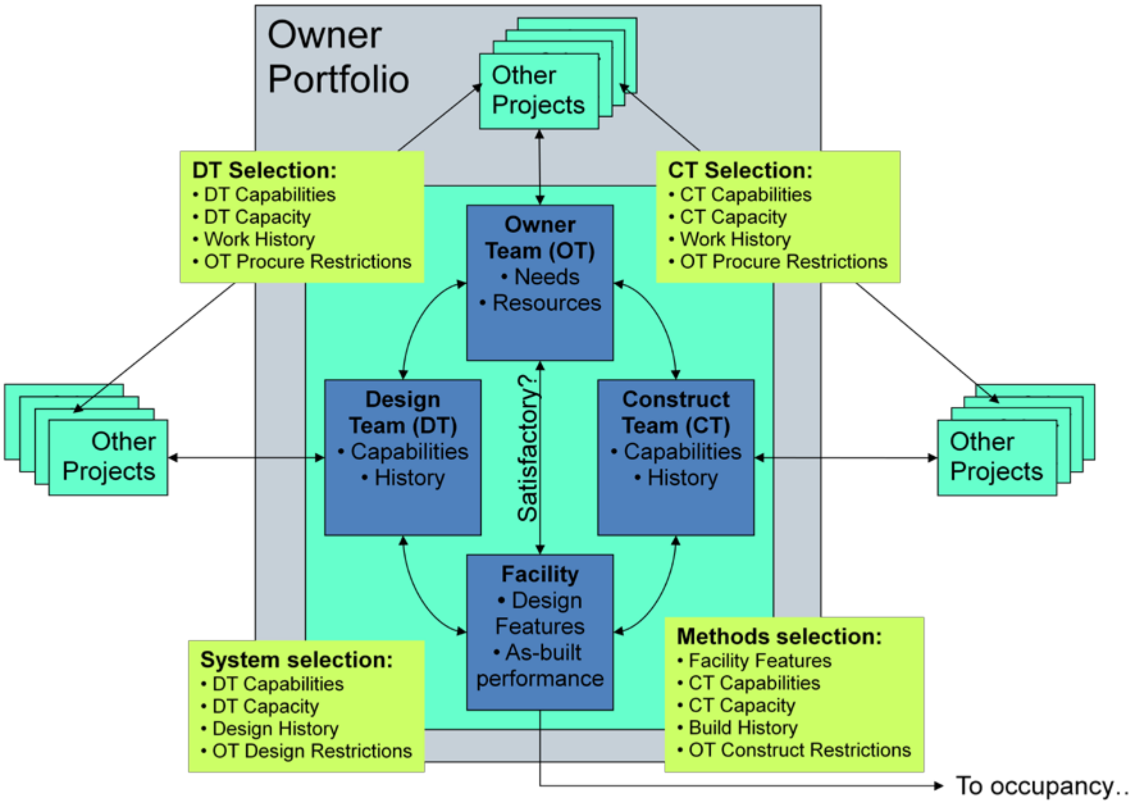

Figure 2: A project-scale model in the context of an owner portfolio involves multiple stakeholders who are also engaged in other projects at the same time

3.2 Total Cost of Ownership at the Portfolio Scale

At the portfolio scale, TCO represents an amalgamation of the TCO for each facility comprising the portfolio, but it is again an emergent property that is more complex than a simple sum of individual facility TCOs. Given that the portfolio as a whole is intended to meet the overall needs of the owner organization, entities within that organization and its sub-organizations can shift utilization of different facilities within the portfolio as appropriate to better meet the overall needs of the organization. In an ideal world, facilities represent fungible assets to the organization that can be applied with no transactional friction to optimize the ability of the organization to meet its mission. In reality, this is far from the case. Even if there were no costs or down time associated with churn of people within facilities, factors such as agency identification with and pride in its physical assets, proximity and convenience of logistics, and the need for a consistent interface with the public being served mean that facilities cannot be considered in isolation from their organizational context. These factors also lead to gaming among facility stakeholders during the funding allocation process, where “getting your building funded” represents a victory for your own agency, even though it may not be an optimal solution from a whole portfolio standpoint (the commons dilemma).

What is the relationship between funding allocated to the project and the total cost of ownership (TCO) of that project over its lifecycle, given the way projects are delivered and utilized in the public sector? Does more funding reduce TCO? Does less funding increase it? In the context of a whole portfolio, less funding to each individual project means that more total projects can be funded, given a fixed budget allocation for capital projects. At the same time, there are minimum funding thresholds beneath which viable projects that meet owner requirements simply cannot be delivered. Moreover, little is known about how a generic cost premium would be used within a sustainable project if it were not explicitly targeted to a specific cost item. There is a need to better understand the relationships between initial investments in individual projects and the TCO of those projects as a basis for understanding how to most effectively allocate funding for capital projects, given the goals of minimizing TCO while meeting agency requirements.

4 AN AGENT-BASED MODELING APPROACH TO TCO

From a modeling standpoint, capturing the complexity of the socio-enviro-technical system that is a capital project presents a challenge. Even in classic design-bid-build project delivery, a project's installed cost is a function of market conditions and the behaviors of human individuals and organizations as much as it is the scope of the project. The objective of this research was to evaluate whether an agent-based modeling approach could be effectively used to simulate the behavior of this complex system at key phases of the life cycle of a capital project so that the ultimate total cost of ownership for the facility can be predicted more accurately and realistically than the simple cost margin approach used by institutional owners today.

The approach taken in this project employed a broader perspective on project cost that is cognizant of the complex relationships between people, technology, and context that influence TCO over a facility's life cycle. Agent-based modeling (ABM) allows the simulation of this complex system and the emergent properties of the system, specifically TCO. An ABM approach is both modular (with model components able to be developed sequentially and replaced over time as new empirical data is obtained) and scalable (able to be combined into a larger ABM that represents portfolios of projects), thus providing the ability to evaluate scenarios at the facility and portfolio scales.

4.1 Design Concepts for the Facility-Scale TCO Model

One of the most significant aspects of the research to date has been determining how to conceptualize the project in a way that can be modeled effectively and tied to existing cost models. Ultimately, various ways exist to frame the problem of predicting TCO. Existing approaches to life cycle costing can, with proper assumptions and sufficient information, reasonably predict such a metric. The real challenge lies in making good assumptions at the conceptual stage of a project when relatively little is known about the project design, implementation, or use. Rather than reinventing existing approaches to costing, the focus of this research has been to use an ABM model to generate detailed inputs to existing cost models that can then be used to generate actual TCO estimates.

To accomplish this aim, the overall project life cycle was divided into four major phases encapsulating critical decisions affecting TCO: project team formation, design, construction, and operations. The possible agents that could be included in the model have also been defined at a comparatively coarse resolution (owner, design team, construction team), with the intent of later refining each module to capture agent interactions at a higher level of detail after initial feasibility was established. Table 1 shows the interactions among agents within each of these four segments. Note that each major stakeholder group (owner, designer, constructor) is likely to be involved in multiple projects at once and over time, and each group also consists of a variety of individual agents acting purposively within the organization. These more detailed agent interactions are a target of future research. ABM models can be constructed in a hierarchical fashion to enable additional levels of detail to be added as the model development proceeds.

Table 1 also reflects the decision made by the research team to model the technological components or assemblies comprising the facility as agents themselves during the design phase to reflect the thought process of the designer in making system selection decisions. The next section describes the rationale for this decision in more detail.

Table 1: Various entities are involved in the planning, design, construction, and operations/maintenance (O&M) of a capital facility during its life cycle.

	Team Formation	Design	Construction	O&M
Owner/User	Specifies project need and feasibility constraints; chooses design/construct entities for the project from those circulating in the market at the time of selection	Reviews and approves or rejects system selection decisions based on past experience (if any) with each system	Observes installation of systems, which influences experience with component technologies for future projects; approves substitutions if required during construction	Interacts with facility technologies in ways that result in operations or maintenance costs; adjusts opinions of components that will influence selection on future projects
Designer	Responds to relevant project opportunities as long as capacity exists; selection attributes include design philosophy and past experience with similar projects	Develops configurations of building systems to improve upon prototype design supplied by owner; influences these configurations based on past experiences with component systems	Observes installation of systems, which influences experience with component technologies for future projects; supplies substitutions if required during construction	Not involved except for possible feedback on systems performance and client satisfaction with design decisions
Constructor	Responds to relevant project opportunities as long as capacity exists; selection attributes includes past experience with similar projects	Supplies price information for design scenarios based on prior experience and market conditions	Coordinates installation of systems using subcontractor and supplier agents; costs based on market condition and prior experience with each component type	Limited involvement for callbacks to handle warranty issues; no influence on cost
Building Components	Not involved unless modeling resource scarcity issues in the market	Gravitate toward or away from prototype design within decision space; are either rejected or incorporated based on whether they can improve performance and "greenness" without violating constraints	Pair with subcontractor and supplier agents to be procured and installed on project, subject to market constraints; may provide a positive or negative experience for associated agents	Interact with owner/user agents to result in operations and maintenance costs such as energy use, water use, component repair and replacement, etc.

4.2 Example: Developing a Specification for the Facility Design Module

One example of the approach taken in this research to defining the functionality of the ABM is the development of the design module. Suppose that the primary agents in the design-phase model are assemblies representing individual building systems such as foundations or flooring, or sustainability-related technologies or practices such as rainwater harvesting system or on-site recycling. These agents are observed by (and exchange information with, in various ways,) the three primary human agents for a specific project: the designer, the constructor, and the owner. An assembly in this case was defined as any set of building practices or components with an identifiable function that might be implemented by a subcontractor as part of a project. The UNIFORMAT II classification of building elements and related sitework (see http://www.uniformat.com/classification-of-building-elements.html) was used to determine which assemblies to include.

To bound the design process for initial model development, the process of prototype-based design was used. Prototype design is an approach used by institutional owners with many projects of similar type or function to obtain consistent buildings across multiple projects. Prototype design is used by both public sector owners such as the U.S. Postal Service or the State of Georgia school system, and private sector owners such as banks with multiple branches, hotels, and big box stores. In this approach, design prototypes are created that specify the basic systems for a particular building type. In each project situation, the prototype serves as a starting point that is customized to meet specific site conditions.

For the ABM under the assumption of a prototype design process, there exists a base prototype building that consists of a predetermined set of compatible assemblies of different types that can be supplemented or replaced by other assemblies "floating" around in the decision space. Each of the assemblies has, at a minimum, a total installed cost, an affinity with respect to the project at hand, and a life cycle cost impact function. Each assembly also has a separate sustainability function to capture externalities or non-quantified costs and/or benefits associated with it. The model begins with the prototype set of assemblies in the center of the decision space, affiliated with each other to form a complete building. Additional candidate assemblies are arbitrarily distributed throughout the space. Depending on the model complexity, the set of available additional assemblies could include both feasible and infeasible options, although this would require additional checking for technological feasibility when substitutions are being considered. This option would be useful if working from a database of assemblies that remained constant from project to project or when considering multiple projects at once such as for a portfolio-scale analysis.

With each iteration of the model, those assemblies not already part of the building change location based on their affinity with respect to the project. In the design phase TCO model, affinity is a function of prior experience on the part of any stakeholder (designer, constructor, owner) with that assembly (either positive or negative), and a contextual appropriateness function based on attributes of the project context. The appropriateness function must be seeded with basic project parameters provided by the user such as climate, development density, etc. to describe the project context. For instance, stormwater management technologies are most contextually appropriate in highly urban areas, so would have a high value for contextual appropriateness for urban projects.

Assemblies with higher affinity for the project move more quickly *toward* the prototype building, while those with lesser affinity move more slowly toward the building, and those with negative affinity move *away* from the building. When an assembly reaches the building, it is compared with the corresponding assembly in the prototype. If the new assembly is *better than* the existing assembly according to the life cycle cost impact function and/or sustainability impact function, it displaces that assembly, which is either discarded or sent back out to the decision space. If it is *worse than* the existing assembly, it is ricocheted back out into the decision space. If there is no corresponding assembly in the building (i.e., if the new assembly would be an add-on rather than a substitution), it could be added to the building scope if it improves any of the objective functions while remaining within the constraints.

Total installed cost of the prototype as a whole (i.e., all the assemblies included as part of the building at any point in time) could be either a constraint or an objective function when determining whether to substitute or add a new assembly. Within the decision space, multiple assemblies can also reach the project at the same time and be accepted based on their joint effects on the prototype building, whereas they might be rejected if they were considered individually. Incoming assemblies should also be able to displace multiple existing assemblies, e.g., a new reflective roof replacing not only the roof but also allowing for downsizing the building cooling system as well. This can be represented either by (a) representing sized systems such as air conditioning (AC) systems using multiple assemblies (e.g., multiple tons of AC capacity), with some being displaced but not all to represent downsizing, or (b) by having a better assembly displace both the existing corresponding assembly as well as any related assemblies, resulting in an incomplete facility until an alternate assembly is found for the building that would fit the new situation. If the simulation ends before an alternate is found, the substitution would have to be reversed to ensure that the building scope is complete.

Total installed cost for an assembly is determined by querying the constructor agent whenever that assembly reaches the location of the building. The cost of that assembly could be approximated stochastically to reflect varying market conditions each time the query is made, or could be seeded with an average value. It could also be a function of the contractor's past experience with the assembly. Contractor response to a cost query is a separate module to be developed in future research in more detail and may be a function of market conditions, subcontractor relationships, procurement requirements, prior contractor experience with the products, and other factors.

Life cycle cost impact is determined by querying the owner agent whenever an assembly reaches the location of the building. The life cycle cost of that assembly could be approximated stochastically each time the query is made. Owner response to a cost query is a module to be developed in future research in more detail, and may be a function of expected use of the facility, availability of maintenance resources, and other factors to reflect uncertainties associated with future building use or changes in resource prices.

Other sustainability impact is determined by querying the designer agent whenever an assembly reaches the location of the building. This objective function is necessary to capture some of the externalities that drive system selection decisions, such as visibility/prestige of "greener" finishes, overall societal benefits, and others. The LEED rating system encourages behaviors that have better performance with respect to economic externalities, so it may be a reasonable approximation of these externalities as well as a widely recognizable metric used by industry stakeholders.

When the model reaches a steady state, the sum of the total installed costs of all assemblies is the first cost of the project, and the sum of the life cycle costs of all assemblies is the life cycle cost of the project. The sum of these two represents the total cost of ownership of the facility as estimated at the end of the design phase. The configuration of assemblies comprising the design then feeds into subsequent modules for construction and O&M to further refine the cost estimate.

This representation approximates a construction management approach to a project. For a design-bid-build approach, constructor bids could be determined using the total installed cost query function for all assemblies together for a complete building scope. That scope could be specified in advance by the user, or could be determined in other ways as well such using the prototype design without modification.

4.3 Results to Date

To date, conceptual models have been developed for project team formation and design. Detailed models for construction and operations are under development as part of future research. The process for determining model functionalities and structure has involved developing a basic strawman of system performance based on literature review for the behaviors and functional relationships among key agents, followed by adjustment and validation using stakeholder interviews and field observations. Partner organizations for the project include the U.S. Postal Service (see Ahn 2010 for more information) and the U.S. Naval Facilities Command.

The approach to model development was based on a hierarchy of cascading complexity. Starting at the individual project scale, the fundamental agents were defined at a low resolution and a working model was developed at this resolution before more detail was introduced. As the composite model is developed, it is verified against cost data for prototype projects using various green technologies and practices developed through simulation and validated against project data from partner organizations (ibid.). Development of modules to represent increasing levels of detail is part of further research to be conducted in subsequent years of the project.

5 THE FUTURE: USING MODELING TO OPTIMIZE POLICIES AND DECISION MAKING

The initial results of using agent-based modeling to predict TCO are promising. An ABM approach offers the ability not only to nest models within models to capture the behavior of individuals within organizations, but also to scale up the model as a more complex representation of the marketplace. Ultimately, the aim is to develop a larger scale model that can simulate the effects of public policy on diffusion and adoption of sustainability-related technologies and practices. For instance, the relationship between initial investments in high performance facilities and their overall lifecycle performance is a challenge on the scale of both individual facilities and the portfolios of which they are a part, since resources available to those portfolios are ultimately finite and must be allocated effectively and fairly among projects to optimize agency outcomes. A portfolio-scale model of TCO based on individual facility models could serve as a basis to understand the impacts of uniform vs. differential investments in green building. For example, are the best results achieved by allocating X% more funds to improve the energy performance of all projects, or should the total amount be focused on a Pareto subset of projects that are likely to have the greatest impacts? While intuition may tell us that the latter strategy will be more effective, what impact does it have on human behavior associated with facilities that are *not* exceptional? Is less attention then paid on those projects to meeting energy efficiency goals?

Such a model could also provide a perspective on the most effective way to mandate action to improve overall portfolio performance. For instance, are prescriptive requirements for building improvement most effective (e.g., “all facilities must use technology X”)? Or are performance-based requirements (e.g., “all facilities must use whatever technologies are appropriate to achieve energy reduction Y”) likely to be more effective in influencing overall performance across a portfolio?

Being able to accurately model the response of coupled technological and human systems to policy intervention through simulation will provide a better approach to policy design that permits experimentation without the risks inherent in policy trial and error on a full scale. Ultimately, the outcomes of this research will further the goals of sustainability in public sector capital projects by providing a more realistic and accurate picture of the relationships between investment and outcomes, and generating the knowledge that is needed to direct limited resources where they can do the most good.

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REFERENCES

Ahn, Y.H. (2010). *Sustainability Investments for Capital Project Portfolios.* Ph.D. Dissertation, Environmental Design and Planning, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Ahn, Y. H., and Pearce, A. R. (2007). "Green Construction: Contractor Experiences, Expectations, and Perceptions." *Journal of Green Building*, 2(3), 106-122.

Ahn, Y. H., Pearce, A. R., and Ku, K. H. (2009a). "Green Construction: U.S. Contractors’ Status and Perception." *Proceedings of International Conference on Construction Engineering and Management (ICCEM)*, Jeju, Republic of Korea.

Arditi, D.A. and Messiha, H.M. (1996). “Life-cycle Costing in Municipal Construction Projects,” *Journal of Infrastructure Systems,* 2(1), 5-14.

Arpke, A. and Hutzler, N. (2005). “Operational Life-cycle Assessment and Life-Cycle Cost Analysis for Water Use in Multioccupant Buildings,” *Journal of Architectural Engineering,* 11(3), 99-109.

Asiedu, Y. and Gu, P. (1998). “Product life cycle cost analysis: state of the art review,” *International Journal of Production Research*, 36(4), 883-908.

Baetz, B.W. and Korol, R.M. (1995). “Evaluating technical alternatives on basis of sustainability.” *Journal of Professional Issues in Engineering Education and Practice,* 121(2), 102-107.

Boehm, B.W. 1981. *Software Engineering Economics.* Prentice Hall, Upper Saddle River, NJ.

Bennett, M. and James, P. (1998). *The Green Bottom Line: Environmental Accounting for Management.* Greenleaf Press, Sheffield, UK.

Bray, J. and McCurry, N. (2006). “Unintended Consequences: How the Use of LEED can Inadvertently Fail to Benefit the Environment.” *Journal of Green Building* 1(1), 152-165.

Cole, R.J. (2000). “Cost and Value in Building Green.” *Building Research & Information,* 28(5/6), 304-309.

Dewick, P. and Miozzo, M. (2004). “Networks and innovation: sustainable technologies in Scottish social housing.” *R&D Management,* 34(3), 323-333.

DuBose, J.R. (1994). “Sustainability as an Inherently Contextual Concept: Some Lessons from Agricultural Development.” M.S. Thesis, School of Public Policy, Georgia Institute of Technology, Atlanta, GA.

DuBose, J.R., Bosch, S.J., and Pearce, A.R. (2007). “Analysis of Statewide Green Building Policies,” *Journal of Green Building,* 2(2), 161-177.

EIA. (2009). "Annual Energy Outlook 2009." *Energy Information Administration*, <http://www.eia.doe.gov/oiaf/aeo/overview.html> (February 22, 2009).

Ehlen, M.A. (1997). “Life-cycle Costs of New Construction Materials,” *Journal of Infrastructure Systems,* 3(4), 129-133.

Enermodal Engineering. (2006). *The Cost and Benefits of LEED-NC in Colorado*. Governor’s Office of Energy Management and Conservation, State of Colorado, Denver, CO.

Fisk, W. J. (2000). "Health and productivity gains from better indoor environments and their relationship with building energy efficiency." *Annual Review of Energy and Environment and Resources*, 25, 537-566.

Fisk, W. J., and Rosenfeld, A. H. (1997). "Estimates of Improved Productivity and Health from Better Indoor Environments." *Indoor Air*, 7(3), 158-172.

Fuller, S.K. and Peterson, S.R. (1995). *Life-Cycle Costing Manual for the Federal Energy Management Program – NIST Handbook 135.* National Institute of Standards and Technology, Gaithersburg, MD. Available online at http://www.bfrl.nist.gov/oae/publications/handbooks/135.pdf.

Gil, N., Tommelein, I. D., Kirkendall, R.L., and Ballard, G. (2000). "Contribution of Specialty Contractor Knowledge to Early Design." *Proc. Eighth Annual Conference of the International Group for Lean Construction* (IGLC-8), 17-19 July, held in Brighton, UK.

Goda, K. and Hong, H.P. (2006). “Optimal Seismic Design Considering Risk Attitude, Societal Tolerable Risk Level, and Life Quality Criterion,” *Journal of Structural Engineering.* 132(12), 2027-2035.

Grosskopf, K.R. and Kibert, C.J. (2006). “Developing market-based incentives for green building alternatives.” *Journal of Green Building,* 1(1), 141-147.

Gustafsson, S.I. and Karlsson, B.G. (1987). “Minimization of the life cycle cost when retrofitting buildings,” ICBEM – 87, Vol. II, Pressef Polytechnique Romandes, Lausanne, Switzerland, 163-170.

Hawken, P., Lovins, A., and Lovins, H. (1999). *Natural Capitalism*. Little, Brown and Company, New York, NY.

Hill, R. C., and Bowen, P. A. (1997). "Sustainable construction principles and a framework for attainment." *Construction Management and Economics*, 15(3), 223-239.

Hinge, A., Winston, D., Stigge, B., and Happold, B. (2006). *Moving Toward Transparency and Disclosure in the Energy Performance of Green Buildings*. American Council for an Energy Efficient Economy. Washington, DC.

IFMA – International Facilities Management Association, National Association of State Facilities Administrators, Association of Higher Education Facilities Officers/APPA, Federal Facilities Council, Holder Construction Company, and Infrastructure Strategies. (2008). *Asset Lifecycle Model for Total Cost of Ownership Management: Framework, Glossary, and Definitions.* Available online at < http://www.ifma.org/tools/research/Asset_Lifecyle_Model.pdf>

Jeon, C.M. and Amekudzi, A.A. (2005). “Addressing Sustainability in Transportation Systems: Definitions, Indicators, and Metrics,” *Journal of Infrastructure Systems*, 11(1), 31-50.

Junilla, S. and Horvath, A. (2003). “Life-cycle Environmental Effects of an Office Building,” *Journal of Infrastructure Systems*, 9(4), 157-166.

Junnila, S., Horvath, A., and Guggemos, A.A. (2006). “Life Cycle Assessment of Office Buildings in Europe and the United States,” *Journal of Infrastructure Systems*, 12(1), 10-17.

Kats, G. (2003). *The Costs and Financial Benefits of Green Buildings*, A Report to California's Sustainable Building Task Force, Sacramento, CA.

Kats, G. H. (2004). "Green Building Costs and Financial Benefits." a Report to California's Sustainable Building Task Force, Capital E (www.cap-e.com).

Keys, L.K. (1990). “System life cycle engineering and DF ‘X’,” *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 13(1), 83-93.

Keysar, E. and Pearce, A.R. (2007). “Decision Support Tools for Green Building: Facilitating Selection Among New Adopters on Public Sector Projects,” *Journal of Green Building*, 2(3), 153-171.

Kibert, C. J. (1994). "Principles of Sustainable Construction " *Proceeding of the First International Conference on Sustainable Construction*, Tampa, FL.

Kibert, C. J. (2005). *Sustainable Construction: Green Building Design and Delivery*, John Wiley & Sons, Hoboken, NJ.

Kibert, C. J. (2008). *Sustainable Construction: Green Building Design and Delivery*, 2 Ed., John Wiley & Sons, Hoboken, NJ.

Klotz, L., Horman, M., and Bodenschatz, M. (2007). “A Lean Modeling Protocol for Evaluating Green Project Delivery.” *Lean Construction Journal*, 3(1), 1-18, April.

Koebel, C.T. (1999). "Sustaining Sustainability: Innovation in Housing and the Built Environment," *Journal of Urban Technology*, 6(3), 75-94.

Koebel, C.T., Papadakis, M., Hudson, E., and Cavell, M. (2003). *The Diffusion of Innovation in the Residential Building Industry*. U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, DC.

Koebel, C.T. (2004). "Housing Technology, Community, and the Economy," in *NSF-PATH Housing Research Agenda Workshop: Proceedings and Recommendations* (Volumes I and II), pp. 66-76, February. Available online at http://www.pathnet.org/sp.asp?id=12201

Lapinski, A., Horman, M., and Riley, D. (2005). “Delivering Sustainability: Lean Principles for Green Projects.” *Proceedings, 2005 ASCE Construction Research Congress.*

Lapinski, A.R., Horman, M.J., and Riley, D.R. (2006). “Lean Processes for Sustainable Project Delivery.” *Journal of Construction Engineering and Management*, 132(10), 1083-1091.

Larsson, N. and Clark, J. (2000). “Incremental costs within the design process for energy efficient buildings.” *Building Research & Information*, 28(5/6), 413-418.

Lechner, N. (2009). *Heating, Cooling, Lighting: Sustainable Design Methods for Architects*, 3 Ed., John Wiley & Sons, Inc, New York, NY.

Liu, M., and Frangopol, D. M. (2006). "Optimizing Bridge Network Maintenance Management under Uncertainty with Conflicting Criteria: Life-Cycle Maintenance, Failure, and User Costs." *Journal of Structural Engineering*, 132(11), 1835 - 1845.

Matar, M.M., Georgy, M.E., and Ibrahim, M.E. (2008). “Sustainable construction management: introduction of the operational context space (OCS).” *Construction Management and Economics*, 26(3), 261-275.

Matthews, J., Tyler, A., and Thorpe, A. (1996). “Pre-construction project partnering: developing the process.” *Engineering, Construction and Architectural Management*, 3(1/2), 117 – 131.

Maxey, D.E. (2006). *An Evaluation of Benefits of Building Commissioning on Capital Projects at Virginia Tech*. Final M.S. Report, Department of Building Construction, College of Architecture and Urban Studies, Virginia Tech, Blacksburg, VA.

United Nations. (2000). *United Nations Millenium Declaration.* Available online at < http://www.un.org/millennium/declaration/ares552e.pdf>.

Migliaccio, G.C., Goel, S., and O'Connor, J.T. (2006). "Life-cycle Cost Analysis for Selection of Energy-Efficient Building Components in Lodging Facilities," *AEI 2006*, 190(54),

Mogge, J.W. (2004). *Breaking through the first cost barriers of sustainable planning, design, and construction.* Ph.D. Dissertation, School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA.

NAVFAC – Naval Facilities Engineering Command. (2007). *Cost Engineering: Policies and Procedures.* Dated 9/6/07. Available online at http://www.uscost.net/costengineering/Documents/policy-procedures.pdf.

NAVFAC – Naval Facilities Engineering Command. (2008). *Navy DD 1391 Sustainable Design Cost Tool.* Available online at http://www.wbdg.org/docs/navy_1391_leed.xls.

Nam, C. H., and Tatum, C. B. (1992). ''Noncontractual methods of integration on construction projects.'' J. Constr. Engrg. and Mgmt., ASCE, 118(2), 385–398.

Nelms, C.E, Russell, A.D., and Lence, B.J. (2007). "Assessing the performance of sustainable technologies: a framework and its application." *Building Research and Information*, 35(3), 237-251.

Newsham, G., Mancini S., and Birt B. (2008). "Do LEED-certified Buildings Save Energy? Yes, but…" *Energy and Buildings*, 41(8), 897-905.

Newton, L.A. and Christian, J. (2006). "Impact of Quality on Building Costs," *Journal of Infrastructure Systems,* 12(4), 199-206.

OECD – Organisation for Economic Co-operation and Development. (2001). *Sustainable Development: Critical Issues.* OECD, Paris, France.

OECD. (2003). *Environmentally Sustainable Buildings: Challenges and Policies*, OECD Publication, Paris, France.

Pearce, A.R. (1999). *Sustainability and the Built Environment: A Metric and Process for Prioritizing Improvement Opportunities.* Ph.D. Dissertation, School of Civil & Environmental Engineering, Georgia Institute of Technology, Atlanta, GA.

Pearce, A.R. (2003). *An Online Knowledge Base for Sustainable Military Facilities & Infrastructure.* Final Project Report to Region IV Department of Defense Pollution Prevention Partnership, University of South Carolina.

Pearce, A.R. (2004). *Sustainability Design Cost Differential Analysis for Constructed Projects Using the LEED Green Building Rating System.* Project report submitted to US Air Force Reserve Command Headquarters, Robins AFB, GA.

Pearce, A.R., DuBose, J.R., and Bosch, S.J. (2007). "Green Building Policy Options in the Public Sector," *Journal of Green Building,* 2(1), 156-174.

Pearce, A.R., DuBose, J.R., Bosch, S.J., and Carpenter, A.M. (2005a). *Greening Georgia Facilities: An Analysis of LEED Requirement Impacts.* Final Project Report to the Georgia Environmental Facilities Authority, Atlanta, GA, September 30.

Pearce, A.R., Bosch, S.J., DuBose, J.R., Carpenter, A.M., Black, G.L., and Harbert, J.A. (2005b). *The Kresge Foundation and GTRI: The Far-reaching Impacts of Green Facility Planning.* Final Project Report to the Kresge Foundation, Troy, MI, June 30.

Pearce, A.R., DuBose, J.R. Bosch, S.J., and Carpenter, A.M. (2005c). *Sustainability and the State Construction Manual: Georgia-specific Voluntary Guidelines.* Final Project Report to the Georgia State Finance and Investment Commission, Atlanta, GA, December.

Pearce, A.R., and Fischer, C.L.J. (2001). *Systems-Based Sustainability Analysis of Building 170, Ft. McPherson, Atlanta, GA.* Summary analysis report to the Army Environmental Policy Institute, Atlanta, GA, May.

Pearce, A. R. (2008). "Sustainable Capital Projects: Leapfrogging the First Cost Barrier." *Civil Engineering and Environmental Systems*, 25(4), 291-300.

Pearce, A.R. and Vanegas, J.A. (2002). "Defining Sustainability for Built Environment Systems," *International Journal of Environmental Technology and Management,* Special Issue on Sustainability and the Built Environment, 2(1), 94-113.

Prowler, D. (2008). "Sun Control and Shading Devices." <http://www.wbdg.org/resources/suncontrol.php> (April 15, 2009).
Pulaski, M.H. and Horman, M.J. (2005c). "Organizing Constructability Knowledge for Design." *Journal of Construction Engineering and Management*, 131(8), 911-919.
Pulaski, M.H., Horman, M.J., and Riley, D.R. (2006). "Constructability Practices to Manage Sustainable Building Knowledge." *Journal of Architectural Engineering*, 12(2), 83-92.
Pulaski, M., Pohlman, T., Horman, M., and Riley, D. (2003). "Synergies between Sustainable Design and Construction at the Pentagon." *Proceedings, 2003 ASCE Construction Research Congress.*
Ravirala, V. and Grivas, D.A. (1995). "State Increment Method of Life-cycle Cost Analysis for Highway Management," *Journal of Infrastructure Systems*, 1(3), 151-159.
Reed, W.G. and Gordon, E.B. (2000). "Integrated design and building process: what research and methodologies are needed?" *Building Research & Information*, 28(5/6), 325-337.
Riley, D., Pexton, K., and Drilling, J. (2003). "Procurement of sustainable construction services in the United States: the contractor's role in green building." *UNEP Industry and Environment*, 26(2/3), 66-69.
Rogers, E.M. (2003). *Diffusion of Innovations, 5th ed.* Free Press, New York, NY.
Rohracher, H. (2001). "Managing the Technical Transition to Sustainable Construction of Buildings: A Socio-Technical Perspective." *Technology Analysis & Strategic Management*, 13(1), 137-150.
Romm, J.J. and Browning, W.D. (1995). *Greening the Building and the Bottom Line: Increasing Productivity through Energy-Efficient Design*. Rocky Mountain Institute, Snowmass, CO.
Roodman, D. M., and Lenssen, N. (1995). *A building revolution: how ecology and health concerns are transforming construction*, Worldwatch Institute, Washington, DC.
Russell, S.J. and Norvig, P. 2003. *Artificial Intelligence: A Modern Approach.* Prentice Hall, Upper Saddle River, NJ.
Salem, O., AbouRizk, S., and Ariaratnam, S. (2003). "Risk-based Life-cycle Costing of Infrastructure Rehabilitation and Construction Alternatives," *Journal of Infrastructure Systems*, 9(1), 6-15.
Shah, S. (2006). *Sustainable Practice for the Facility Manager*, Blackwell Publishing, Oxford, UK.
State of Georgia. (2007). *State of Georgia Construction Manual.* Georgia State Finance and Investment Commission, Construction Division, Atlanta, GA. Available online at http://www.scm.ga.gov.
Syphers, G., Baum, M., Bouton, D., and Sullens, W. (2003). *Managing the Cost of Green Buildings.* State of California's Sustainable Building Task Force, Sacramento, CA.
Toole, T.M. (1998). "Uncertainty and homebuilders' adoption of technological innovations." *Journal of Construction Engineering & Management*, 124(4), 323-332.
Torcellini, P.A., Deru, M., Griffith, B., Long, N., Pless, S., Judkoff, R., and Crawley, D.B. (2004). "Lessons Learned from Field Evaluation of Six High Performance Buildings". NREL/CP-550-36290, National Renewable Energy Laboratory, Golden, CO.
Turner, C. (2006). "LEED Building Performance in the Cascadia Region". *Proc., Cascadia Region Green Building Council*. Portland, OR.
Turner, C. and Frankel, M. (2008). *Energy Performance of LEED for New Construction Buildings*. New Buildings Institute. Vancouver, WA.
Ugwu, O.O., Kumaraswamy, M.M., Wong, A., and Ng, S.T. (2005a). "Sustainability appraisal in infrastructure projects (SUSAIP): Part 1: Development of Indicators and computational methods," *Automation in Construction*, 15(2), 239-251.
Ugwu, O.O., Kumaraswamy, M.M., Wong, A., and Ng, S.T. (2005b). "Sustainability appraisal in infrastructure projects (SUSAIP): Part 2: A Case Study in Bridge Design," *Automation in Construction*, 15(2), 229-238.
UNCED. (1992). "The Earth Summit." *United Nations (UN)*, <http://www.un.org/geninfo/bp/enviro.html>, (February 15, 2009). Rio De Janeiro, Brazil.
USDOE. (2008). "2008 Energy Building Data Book." *U.S. Department of Energy*, <http://buildingsdatabook.eren.doe.gov/docs/2007-bedb-0921.pdf> (January 10, 2009).

USGBC. (2007). *New Construction & Major Renovation: Reference Guide*, U.S. Green Building Council, Washington, DC.

USGBC. (2009a). "About USGBC." *U.S. Green Building Council*, <http://www.usgbc.org/DisplayPage.aspx?CMSPageID=124> (April 15 2009).

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

Woodridge, M. 2002. *An Introduction to MultiAgent Systems.* John Wiley & Sons, New York, NY.

Zayed, T.M., Chang, L.M., and Fricker, J.D. (2002). “Life-cycle Cost Analysis using Deterministic and Stochastic Methods: Conflicting Results,” *Journal of Performance of Constructed Facilities*, 16(2), 63-74.

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