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Title: Sustainability and Capital Projects: Modeling the Emergent
Property of Total Cost of Ownership
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Abstract: Investment in sustainability strategies and technologies holds promise for significant cost savings over the operational phase of a facility's life cycle, while more effectively meeting stakeholder needs. However, accurately estimating the first costs of a green project during the early concept development stages is challenging, and effective ways to comprehensively predict potential lifecycle cost impacts of sustainability strategies do not exist. This paper describes a agent-based model (ABM) of the Total Cost of Ownership of green facilities applicable at the earliest stages of concept development. An ABM approach captures the social, environmental, and engineering systems that characterize a facility's life cycle cost. It permits evaluating the impact of the institutional and industry environment on facility life cycle performance, and also captures the cost impacts of tightly coupled facility systems that characterize green design.

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 (e.g., MDG 2000; 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 (Pearce 1999). However, just like their ecological counterparts, complex human-designed systems sometimes exhibit emergent behaviors that make their sustainability difficult to evaluate, especially in situations where the performance of those systems depends on interactions with humans and human systems. The built environment – constructed facilities and infrastructure – is one example of this kind of complex system. Not only does the behavior of the system change over time as a result of interacting with different humans during the life cycle, but the perception of performance by each stakeholder also differs based on their experiences with that facility and past experiences with other facilities having similar attributes (Koebel et al. 2003).

In its most literal sense, sustainability is a system state marked by dynamic stability, where changes to the system are constrained to ensure stability into the foreseeable future (Pearce 1999). This state depends not only on the system itself, but also on the context in which the system operates, and the evolving dependencies between them (DuBose 1994; Pearce 1999; Pearce and Vanegas 2002). Measuring sustainability poses a challenge to those who would use the concept as an objective for decision-making, since measuring the 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. Conventional approaches rely upon indicators believed to reflect system

sustainability. For example, in the realm of the built environment, 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, 2009). While not comprehensive or collectively exhaustive, these indicators reflect critical system behaviors influencing sustainability, such as energy consumption, ecosystem disturbance, and waste generation.

Existing indicator-based approaches to sustainability evaluation have yet to be embedded effectively within decision-making processes 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 for a specific facility that are critical for meaningful decision making. A method 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 address observed implementation barriers that are slowing adoption of sustainability in practice.

Cost-Based Sustainability Measurement

One 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 (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 can then be used as a measure of the facility's impact on an organization's financial success.

Total Cost of Ownership

Total cost of ownership (TCO) is a 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 considers both facility occupancy costs and hard capital costs. The International Facilities Management Association (IFMA) defines TCO as (IFMA 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 differ based on the type of decision making being supported by the calculation (Asiedu & Gu 1998). At the project scale, TCO is often used as a metric for comparing project alternatives as part of planning or design, identifying cost drivers for design changes and optimization, or as a screening criterion for project funding (Arditi & Messiha 1996; Asiedu & Gu 1998; Keys 1990). 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 a 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.

Cost Uncertainty over the Project Life Cycle

When project details have *not* yet been developed, cost metrics are more difficult to develop with any certainty. Boehm's (1981) "cone of uncertainty" reflects the fact that as additional definition occurs for a project, uncertainty about its eventual cost decreases. The true cost of a project is only known when the project is complete. From a TCO standpoint, the cone also applies 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; utility costs change; and expectations for building services evolve.

Given that the decision to pursue a project or not may depend on a preliminary cost estimate, developing reliable cost estimates before investing in project design and development is essential. Conventionally, preliminary estimates for projects at the planning stage are based on historical data from similar projects. However, this approach is less applicable to innovative projects that are substantially different from past projects, and the historical data on green projects remains comparatively small. How, then, should decision-makers accurately develop early-stage estimates of innovative green projects?

Status Quo Approaches to Cost Estimating for Green Capital Projects

Green projects are characterized by several unique qualities: tightly coupled designs and multifunction materials and systems (Riley et al. 2004; Rohrer 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; Rohrer 2001), requirements for additional information and documentation (Lapinski et al. 2005, 2006; Pulaski et al. 2003), and greater involvement and integration of input of later stakeholders in earlier project phases (Cole 2000; Gil et al. 2000; Pulaski & Horman 2005; Pulaski et al. 2006; Reed & Gordon 2000; Rohrer 2001). While some research exists 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 believe that this practice remains largely the same despite new 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., Kats 2003, 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. 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. Second, adding a premium to the project estimate means that even if the project is funded, the incentive to seek cost savings is reduced since the money will be lost if it is not spent, thereby creating a self-fulfilling prophecy of increased costs for sustainable projects.

Current approaches to costing green projects are thus lacking in several ways. First, methods for estimating the first cost of green projects early in the 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. Second, life cycle cost estimates are dependent upon building performance models that may poorly represent the actual operating costs of green projects (Hinge et al. 2006; Nelms et al. 2007; Newsham et al. 2008; Turner 2006). Finally, the comparatively small pool of cost data on green projects provides a relatively weak basis for parametric approaches to costing green projects (Lapinski et al. 2006). A new approach is needed to account for actual differences between green and conventional projects which 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) take into account all costs associated with facility ownership to enable balanced allocation of resources across portfolios of facilities, rather than sub-optimizing performance of a single project.

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 throughout a constructed facility's lifecycle:

- 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 technical and people-oriented factors. Selection of parties to participate in a capital project is stochastic and influenced by many factors (Keysar & Pearce 2007; Pearce et al. 2005b).
- 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).
- Construction quality/congruence with original design intent (Newton & Christian 2006).
- Availability of new technologies that can be applied to the facility over its lifecycle, resulting in new cost profiles that are different from those assumed during initial design and construction.
- 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).

The Role of Stakeholders as Agents in TCO

Figure 1 illustrates the complexity of relationships among stakeholders developing a facility up to the point of occupancy. In conventional project delivery, the Owner Team (OT) selects the Design Team (DT) and the Construct Team (CT) on the basis of firm capabilities, capacity to perform the work, history with the owner organization, and specific procurement restrictions such as minority business set-asides. Qualified teams may also be selected on the basis of criteria such as low bid or best value (Pearce 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 of other projects. Selection of the project team influences the first cost of a project, since the unique design of a specific project is influenced by the history and experience of each firm. For instance, design teams tend to favor proven technologies over unproven ones (Nam & Tatum 1992). Owner and Construct organizations also favor technologies and practices successfully demonstrated on peer projects (Pearce et al. 2005a; Rogers 2003; Toole 1998; Koebel 1999; Koebel et al. 2003). The ultimate design (and subsequent performance) 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.

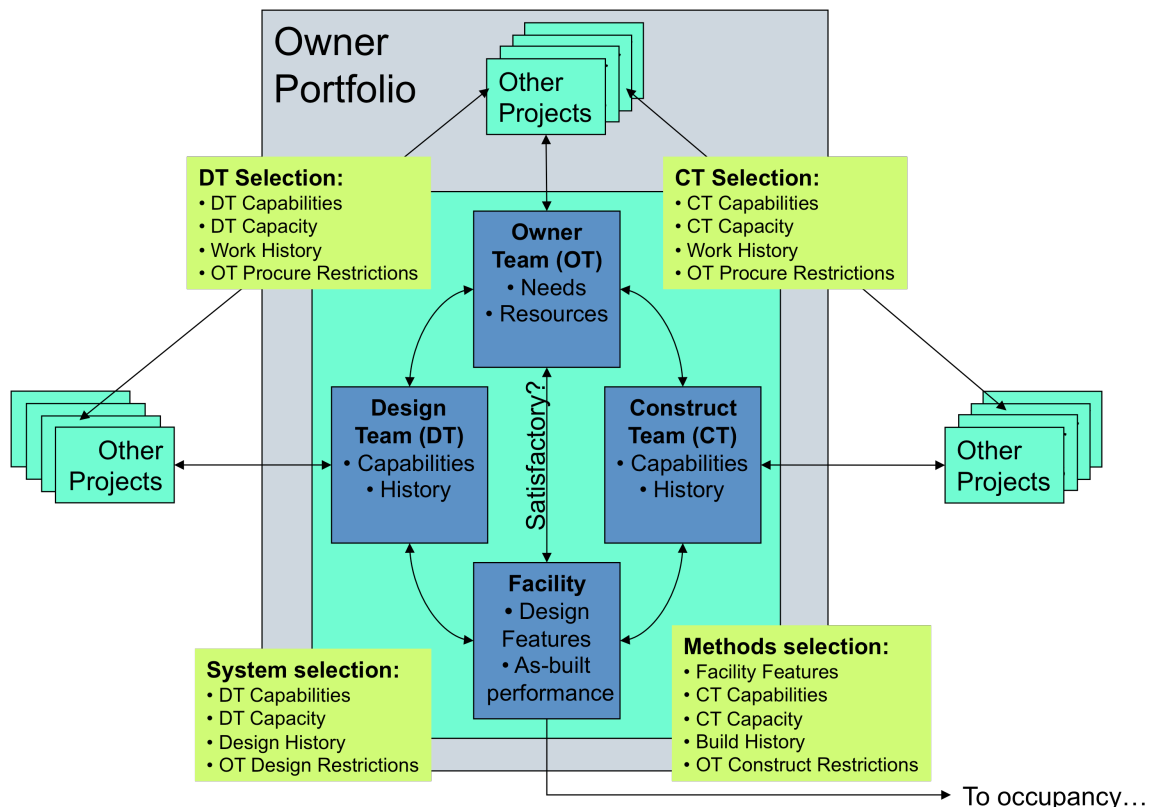


Figure 1: A project-scale model in the context of an owner portfolio involves multiple stakeholders who are also engaged in other projects at the same time

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 the context of a whole portfolio, less funding to each individual project means that more total projects can be funded, given a fixed capital budget. At the same time, there are minimum thresholds beneath which viable projects that meet owner requirements simply cannot be delivered. This research seeks to establish 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.

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. The objective of this research is to evaluate whether an agent-based modeling approach can be used to simulate the behavior of this complex system at key phases of the life cycle of a capital project so that total cost of ownership can be predicted more realistically than the simple cost margin approach used by institutional owners today. The approach taken in this project employs a broader perspective on project cost that recognizes 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.

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. Existing approaches to life cycle costing can, with proper assumptions and sufficient information, reasonably predict TCO. 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. Currently, the agents are defined as collections: owner, design and construction teams. Table 1 shows the typical interactions among agents within each phase. Each major stakeholder group (owner, designer, constructor) is likely to be involved in multiple projects at once and over time, and each group consists of a variety of individual agents acting purposively within the organization. Table 1 also reflects the decision made by the research team to model the facility's technological components or assemblies as agents themselves during the design phase to reflect the decisions made during system selection.

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 systems or on-site recycling. These agents are observed by (and exchange information with, in various ways,) the three primary human agent collections 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 (see <http://www.uniformat.com>) was used to determine which assemblies to include.

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.

To bound the design process for initial model development, prototype design was used. Prototype design is an approach used by institutional owners in both the public and private sectors with many similar facilities to obtain consistent buildings across multiple projects. Examples include the U.S. Postal Service, the State of Georgia school system, 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. The prototype then serves as a starting point that is customized to meet specific site conditions. For the ABM, a prototype building is established that consists of a predetermined set of compatible assemblies of different types that can be supplemented or replaced by other assemblies “available” 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, a life cycle cost impact function, and 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.

With each iteration of the model, assemblies not included in the building design change 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, which must be seeded with basic project parameters provided by the user such as climate, development density, etc. 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 to the decision space. If it is *worse than* the existing assembly, it is returned to 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. 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 operating/use period 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 design-build 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.

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. 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 (Ahn 2010) 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.

The Future: 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 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 green 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 fairly among projects to optimize agency outcomes. A portfolio-scale model of TCO based on individual facility models could help 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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