DELIVERING GREEN BUILDINGS: PROCESS IMPROVEMENTS FOR SUSTAINABLE CONSTRUCTION

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ABSTRACT

The demand for high performance "green" or "sustainable" buildings is rapidly becoming the most significant trend in the building industry. As the Architecture, Engineering, and Construction (AEC) industry develops the strategies and technologies for these projects, an increased emphasis must be placed on the processes and competencies required to deliver high performance buildings. This paper defines an emerging research and education program at Penn State called the Lean and Green Initiative. Focused on understanding all aspects of the delivery of high performance projects, this program is underpinned by established process-based theories and structured around a systematic methodology designed to minimize waste, maximize value, and reduce cost. Current research and educational activities are described in the paper including nine primary research thrusts and their respective goals. Initial results of each research thrust are also provided, providing an early look at the benefits of a process improvement approach to the delivery of high performance buildings.

KEYWORDS

High performance; sustainable building; process; model; improvement

INTRODUCTION

The acceptance and demand for high performance "green" or "sustainable" buildings is rapidly emerging as the most significant and broad reaching trend in the building industry. Both public and private owners are becoming aware of the long term benefits of more healthy and energy efficient facilities.

In the United States, the working understanding of high performance materials, building systems, and design strategies lags behind many of our international counterparts. Currently however, collaboration and research on renewable energy and alternative materials has been reinvigorated, to the point that there exists a multitude of concepts and technologies that can contribute to the dramatic improvements over typical building design and performance.

A widely accepted concept in the design community is that high performance projects require intense interdisciplinary collaboration to ensure that building systems are synergistic and "right sized." The analysis of envelope, lighting, and mechanical systems for example, can no longer take place in a sequential manner, but must be completed in an integrated fashion using advanced analysis and simulation tools that permit the interplay between these systems to be understood and optimized.

As the Architecture, Engineering, and Construction (AEC) industry becomes more adept at understanding the strategies and technologies required on high performance building projects, an increased emphasis must be placed on not just the "what" questions of green buildings, but also the "how" and the "who." In other words, what processes and competencies are required to deliver high performance buildings at the least possible first cost to owners? The answers to these questions will provide important and enduring capabilities currently underdeveloped or missing in high performance building projects. Making high performance buildings first-cost competitive with conventional buildings will significantly improve the attractiveness of these buildings to an industry that (correctly or not) bases many of its decisions on first cost.

This paper describes a focused effort to address the process and competency issues of high performance buildings through an integrated research and education program at Penn State University called the Lean and Green Initiative. High performance green buildings present many challenges and demands that impact projects by increasing process waste and project costs. The development of process-based strategies and techniques will help to deliver high performance buildings at the least possible first cost to owners. Owners are in the best position to influence the success of high performance buildings making them a prime audience for this program. It is owners who will drive change by making use of an improved business model for high performance buildings.

The theory underpinning high performance project delivery is that reduced process waste is able to enhance both sustainable outcomes and the business case for sustainability. Termed "lean and green," waste-reducing principles of lean production are woven together in this program with sustainable strategies of green development. Key to integrating these areas to achieve effective outcomes is a rigorous understanding of the processes of high performance building projects. This program draws on the integrated building process model to provide this capability.

This paper outlines a research and education program assembled to examine how high performance processes can be developed to support the delivery of sustainable projects. The program is informed by detailed research thrusts dispersed throughout the building process supply chain, from owners to contractors to operators of green buildings. The innovative program is outlined, and research and educational features are highlighted to expose the rich potential for advancing high performance project delivery aimed at transforming the building industry.

HIGH PERFORMANCE BUILDING DEFINITION

"Sustainable" or "green" buildings are designed and constructed with emphasis given to environmental, social, and economic priorities. Importantly, they emphasize long-term as well as short-term performance. However, high performance buildings place particular emphasis on building energy use and indoor environment quality. The U.S. Department of Energy (2004) defines high performance buildings as those (emphasis added) "with energy, economic, and environmental performance that is substantially better than standard practice. Their *energy efficiency* saves money and natural resources. The buildings are a *healthy* place to live and work for occupants and have a relatively low impact on the environment."

Notably, not all sustainable or green buildings are high performance, as sustainable accreditation can be achieved by focusing on capabilities other than energy efficiency and indoor environment quality. Equally, some buildings emphasize energy efficiency and indoor environment quality that have not obtained sustainable accreditation. Nonetheless, these buildings have attributes of high performance. Figure 1 illustrates how high performance buildings relate to other classes of buildings by having the high performance building subset extend outside the green building subset to include other buildings. The high performance distinction is an important parameter for this research program because the pursuit of energy efficiency and indoor environment quality substantially affects the design and construction processes of a project. For instance, a major part of design is energy modeling which often increases design iteration and therefore

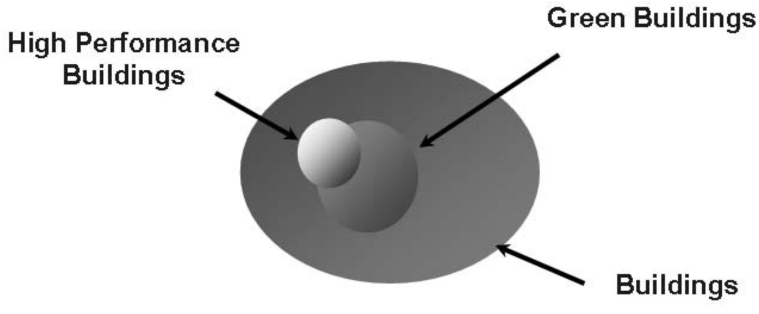


FIGURE 1. Defining high performance buildings.

expense. In construction, added expense and attention are paid to prevent contamination of ductwork. These types of changes are important, and potentially very costly to the project if not performed properly.

AN INTEGRATED HIGH PERFORMANCE BUILDING PROCESS MODEL

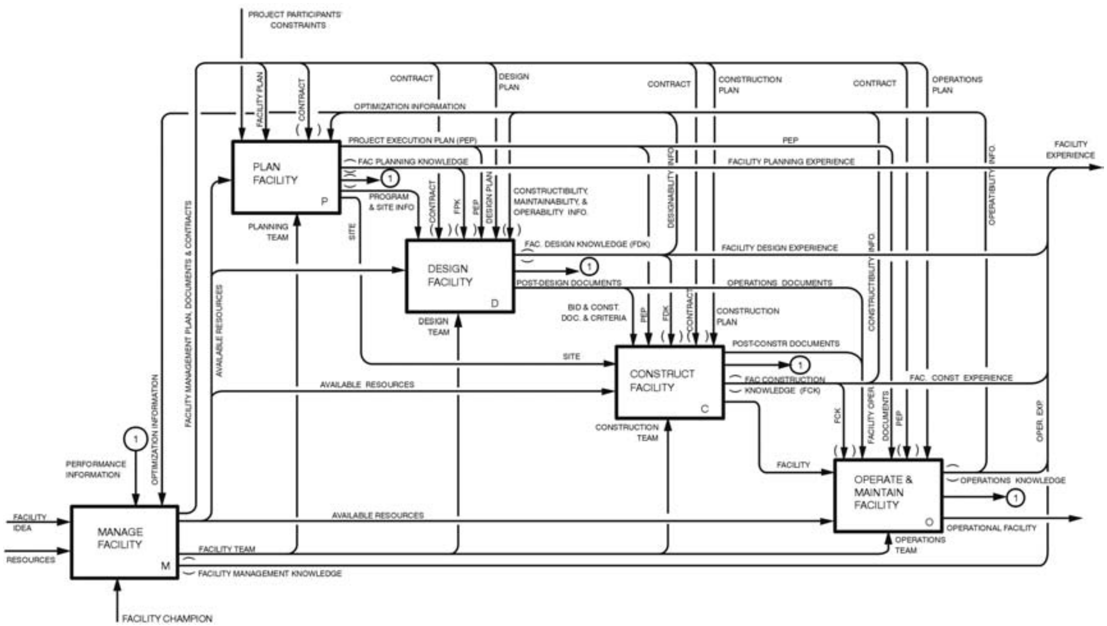
A building process model defines the essential functions required to provide a facility to the end user (Wallace et al. 1987). Building process models emphasize important information, relationships and/or elements concerning the *provision* of the facility. Information about "what" is built, as might be shown in an architectural rendering, is less relevant. Critical are the steps of "how" the facility is constructed and "who" provides the necessary competencies to do so.

The high performance project delivery model that forms a pillar for this research and education program builds on early research at Penn State that developed the Integrated Building Process Model (IBPM) (Sanvido 1990). This model uses the IDEF0 modeling language (ICAM 1981) to identify the managing, planning, design, construction, and operation steps of the life cycle of a facility. Figure 2 shows the basic components of the IBPM at the highest level. The model identifies critical information about the steps of the building process in ways that concern the management of the project. The power of this model comes from a disciplined, systematic approach to describing the complete process of designing and constructing a facility. Notably, the IBPM has been the foundation for extensive research into how projects are completed. For instance, it provided the basis for the industry-changing CII study on the impact of project delivery on project performance (Sanvido and Konchar 1997).

In the high performance building process model, the current IBPM is adapted with additional elements needed for understanding high performance building project processes. These additional elements concern the following.

- **Value and waste generating characteristics:** The first step to integrating lean principles into high performance projects is modeling the waste generating characteristics of a process. The current IBPM defines essential project activities, but does not articulate the value and waste they embody. Without this information, projects tend to adopt wasteful practices. For example, Horman and Kenley (2005) showed that projects average 50% wasted activity.

FIGURE 2. Integrated building process model. Source: Sanvido (1990).



- **Integration of environmental objectives:** In high performance buildings, the environment is elevated to be a key stakeholder of the building along side that of the customer (building owner or user) (Lapinski et al. 2005). Conventional projects, on which the IBPM is modeled, set objectives for the building owner and user, but rarely address the needs of the environment explicitly. The disclosure of environmental objectives makes activities critical that were otherwise thought to be marginal (i.e., wasteful), e.g., energy modeling, life cycle cost analysis.
- **Competencies requirements for the project team:** High performance building projects make critical demands of the project team. Design, for example, must be completed with close attention to component integration in order to achieve required levels of building performance. Critical competencies at required points need to be mapped for high performance building projects in order to understand where to leverage the greatest influence and avoid wasteful activities.

A process model provides the basis for developing important understanding about the characteristics of high performance building delivery.

METHODOLOGY: OVERVIEW OF LEAN & GREEN RESEARCH PROCESS

The integrated high performance building process model provides a common methodology for conducting research. The Lean and Green Initiative seeks to apply value-adding and waste-reducing strategies to the capital project delivery process throughout the life cycle of planning, managing, design, construction, and operation. Focused efforts throughout this lifecycle target areas of improvement that are critical to the delivery of high performance buildings. The common methodology followed through each of these research focus areas includes four research steps.

Step 1: Process Identification

Processes that lack sufficient definition in the project delivery process, and that have the potential for high impact on the delivery of high performance facilities are identified, for example, the integrated design process. Challenges are identified through exploratory research that "diagnoses" the delivery process, and are articulated by owners and project teams experienced in high performance projects about needed improvements.

Step 2: Process Mapping

Through case study analysis and application of lean theory, these processes are mapped in more detail than currently defined. Key processes are added that have been proven to impact the delivery of high performance facilities, and established modeling methodologies, such as IDEF0, are used to represent newly defined High Performance Processes.

Step 3: Process Validation

High Performance Process Models are evaluated through three techniques: 1.) Capability for improvement of current practice by reducing first and/or life cycle cost; 2.) potential to improve the performance of the facility with an emphasis on energy use; and 3.) reduction of downstream process waste. Validation techniques include case studies, historical high performance project delivery data, and an applied program in which the research team participates in the planning, design, construction, and commissioning of an actual high performance facility.

Step 4: Process Guidelines—Dissemination of Results

Research results are formulated into useable guidelines that contribute to the evolving understanding of high performance project delivery. Target audiences for these guidelines include federal and private facility owners. These guidelines are formatted into advisories for owners and accompanying PowerPoint presentations. The guidelines and the research that led to their formulation are being published in leading scholarly journals. Where appropriate, specific products such as project management milestone maps, field guides and handbooks will be developed and made available to industry. In addition, presentations of the research results (e.g., at USGBC's Greenbuild conferences) and company seminars are also used to disseminate results to industry organizations.

SUMMARY OF RESEARCH AND EDUCATION PROGRAM

Utilizing theories and modeling strategies that emphasize and enhance the process of delivering high performance buildings, research and education projects are being pursued under the Lean and Green Initiative throughout the lifecycle of the capital project delivery process. Figure 3 shows the nine research thrusts being pursued. Each project is described in the following sections, including respective research goals and initial findings.

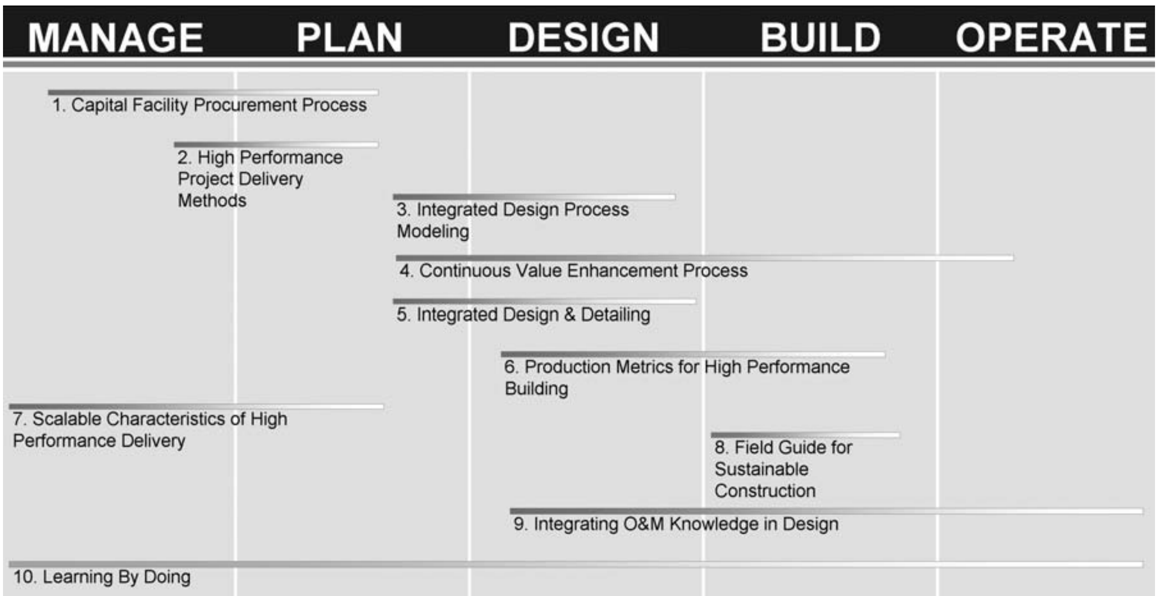
1. Capital Facility Procurement Process

Research Goal Driven by business imperatives realized through reduced operating costs, increased occupant productivity, and higher rental margins, corporate facility owners are increasingly making use of high performance buildings to provide their facility needs. For instance, in 2000, 12 pilot projects were awarded LEED certification; now there are 2,444 projects registered under LEED and 267 that have been certified (LEED 2004). However, to achieve their performance benefits, additional requirements are needed in the delivery processes for high performance buildings. For example, they require intense interdisciplinary collaboration, highly complex design analysis, and careful material and system selection, particularly early in the project delivery process (Riley et al. 2004). Conventional project delivery strategies are not always sufficient for high performance projects. Without a clear understanding of the nature of these project delivery issues, owners frequently encounter high project costs on high performance building projects (Smith 2003).

The Toyota Motor Company provides an example of the use of innovative project delivery to meet the rigors of high performance building delivery. Recognizing the significance of their recently completed LEED gold certified South Campus project, delivered *without* a first cost premium, the Toyota Motor Company sought to capture the essence of their project delivery capabilities. Penn State researchers embedded themselves in the operations of the Toyota Motor Company in order to map and understand the project delivery processes employed. Coupling the Integrated High Performance Building Process Modeling methodology with lean mapping techniques (Liker 2004), the lifecycle of Toyota's delivery process was mapped. This research activity provided unprecedented access and detail of the nature of the Toyota development process. This case study showed Toyota to be a typically structured corporation that was acutely aware of their processes and open to innovation.

Key Findings Detailed process maps at increasing levels of detail were developed of the Toyota develop-

FIGURE 3. The high performance building integrated research and education program.



ment process (Lapinski 2005). The detail of these maps allowed evaluation of the value-generating and waste-laden properties of each process (Horman et al. 2005). The process maps showed that Toyota's key capability at economically achieving sustainable objectives stemmed from: 1.) Their decision to evaluate and adopt sustainable objectives very early in the process, even as early as capital budgeting; 2.) the alignment of sustainable objectives to the business case of the project; 3.) the identification and pursuit of building features that naturally aligned with sustainability; 4.) the selection of an experienced design and construction team early in the project, and 5.) investing time to align individual team member goals with project goals. The seamlessness of this approach is demonstrated by the fact that Toyota adopts precisely the same process regardless of whether projects pursue LEED certification or end up with few sustainable features.

Of equal or greater significance to these identified capabilities are the findings that the Toyota development process has room to improve. Key findings of the research in this area included: 1.) Strong resonation with the lean insights of Spear and Bowen (1999), that one must first understand the total process before truly improving it; 2.) a rigorous process modeling approach enables systematic evaluation of the capabilities of an organization at delivering projects; and 3.) the approach also enables a deeper understanding of improvement impacts. Drawing on a core lean strategy that uses the scientific method to test and evaluate improvement ideas (Spear and Bowen 1999, Spear 2004), an Improvement Ideas Filter was developed through the research to test and focus improvement efforts. Aligned with corporate business objectives, lean principles of continuous improvement, and environmental goals, the filter was tested by implementing ideas on projects and their impact observed. Summarizing the key improvement ideas that were tested at Toyota, Table 1 explains the revisions that were made to the Toyota development process, and highlights the resulting impact.

2. High Performance Project Delivery Methods

Research Goal Project delivery and contracting strategies define how project teams form, their working relationships and levels of involvement, and the incentives offered to team members to contribute their expertise to the project. Although it is widely accepted in the green building community that integrated design and inclusive project teams are essential for green building projects, little discussion has been devoted to the effects of project delivery systems on green building projects.

First introduced by Ballard (2000), the concept of lean project delivery focuses on the integration of design and construction, and the elimination of waste in the design and construction process. The lean and green research thrust in project delivery focuses on defining the attributes of delivery methods in which lean, waste reducing practices help contribute to achieving green goals on building projects. Building upon the critical project delivery research project conducted by Konchar and Sanvido (1998) that developed metrics for project delivery and compared the differences between design-bid-build, design-build, and CM at Risk, this research will focus on the delivery techniques used on completed high performance buildings. Currently in progress, the first phase of this research will be used to gather potential cases study projects and survey participants. Targeted projects include those listed on the USGBC LEED Certified Project list, and the Department of Energy High Performance Building Database. The next phase of the research will be used to collect and analyze detailed information about the delivery of case study projects, including cost and schedule performance metrics, the timing of involvement of key project team competencies, and the achievement of green goals. The final phase of this research will seek common threads among the best performing projects found in the study. The results of this final phase will shape a guide for owners and the design-construction community for the cost-effective delivery of high performance buildings.

Key Findings Preliminary case studies have identified the value of integrated forms of project delivery on green building projects (Korkmaz 2005). The use of design-build delivery, best value contracting, and inclusive open communication strategies on project teams have each been found to contribute directly to the achievement of green goals with the least possible first cost. Conversely, traditional forms of project delivery used on some case study projects, combined

TABLE 1. Process improvement ideas at Toyota.

Improvement Idea	Process Revision	Procedure	Benefits
Effectively capture project successes, opportunities for improvement, & lessons learned	Revise the Post Project Evaluation (PPE) process	Phased PPE. Evaluation of project performance conducted at the end of design and end of project construction via survey. Results shared with project team. Project team then resolves any issues.	Project successes and lessons learned identified early and shared. Issues resolved before they hamper project performance.
Better manage project expectations	Project delivery plan	Simplified process map of critical activities. Presented and discussed at project kickoff meeting. Copies left with team to act as a guide throughout project.	Positively managed project team and end user expectations. Demonstrates when key information is needed for decision making. Improved performance.
Streamline the capital budgeting process	Include and utilize a workplace strategies during capital budgeting	Perform early needs assessment. Generate high level program. Feed this information into the capital budgeting procedure.	More accurate capital budget numbers. Better understanding of initial project costs. Higher success rate of project approvals.
Integrate the delivery process continuum	Creation of the RE&F portfolio manager	Portfolio manager accountable for each phase of delivery process. Follows project from inception through operations.	Reduced number of process handoffs. Improved communication and coordination. Correct resource and capability alignment.
Improve the second delivery process transition (substantial completion—facility operations)	Conduct a project closeout meeting.	Discusses close out procedures. Distribute close documents. Discusses PPE results. Resolve any outstanding issues.	Improved communication and project closeout results. Increase customer satisfaction. Prompt issues resolution.

with inexperience project teams, have been found to contribute directly to wasteful project results that often result in the stripping of green features from buildings in cost-saving measures. The top three mistakes found on these initial case study projects leading to lost value have been identified as (Riley and Horman 2005): 1.) Attempting to change a traditional project to a green building mid-stream; 2.) treating green building features as add-ons to a building initially designed with traditional values; and 3.) poor coordination of energy consultants and considerations for energy use during pre-design stages of projects. Research in progress will be used to evaluate these and other features of project delivery through a more thorough analysis of the delivery practices used on green building projects.

3. Integrated Design Process Modeling

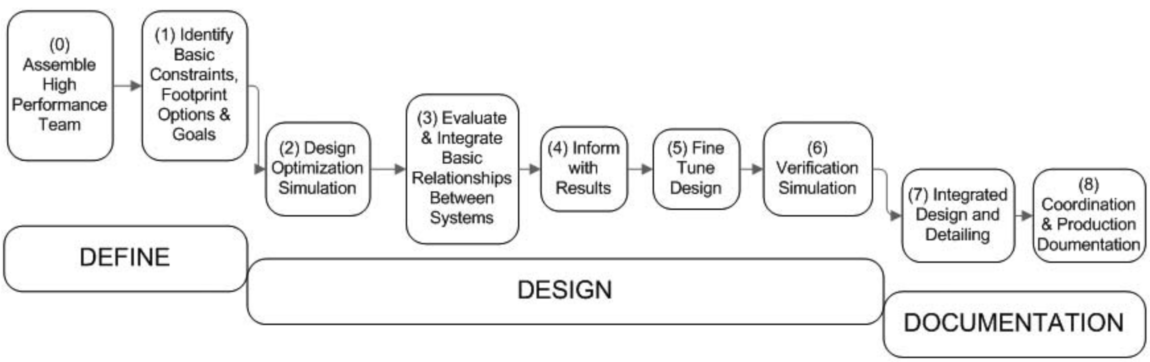
Research Goal The design process for buildings is largely fragmented and disjoint, and is often described with a coarse set of ambiguous milestones such as "schematic design" and "design development" (Magent et al. 2005). Even design teams that strictly follow industry standard design procedures must judge the detail of what is included or not in each phase of design, and often follow their own company approach. Traditional contracting strategies encourage isolated and sequential design steps, which lack integration, and minimize iterations of design that could be used to refine and fine tune building performance. By contrast, *integrated design* processes for high performance buildings require increased cross-disciplinary teamwork throughout the design process (NIBS 2005). In addition, integrated design places an emphasis on increased iterations of simulation and analysis using tools such as energy modeling and day lighting simulation software. Although integrated design is widely accepted as a key element of high performance green buildings, little guidance or defined research exists on how to achieve it, and the key milestones and processes that characterize effective integrated design processes. Fundamental models of engineering design also fall short of describing the nature of the design process as a network of sequenced decisions and analysis functions. In addition, interactions are increased between project team members, making interpersonal skills critical to success (Reed and Gordon 2000). This suggests that competence in the integrated design process includes the ability to interact effectively with other disciplines.

Building upon early models of the integrated building process by Sanvido et. al. (1990) and lean models for design such as concurrent engineering and set-based design, this research thrust will define key processes and competencies of the integrated design process for high performance green buildings. With a particular focus paid to the design of the building envelope and mechanical systems, this research will develop a tool for evaluating the design process as a set of commitments requiring key competencies. Attributes of integrated design will be characterized as those that allow for maximum building performance *and* minimum lost value throughout the process.

Key Findings An early model of the integrated design process has been developed through the integration of both high performance case studies, roundtable discussions with leaders in the green design community, and literature review (Magent et al. 2005). At its highest level, this model presents the design process in three critical stages of Define, Design, and Document. Each of these stages is subsequently broken into a set of iterative processes, each requiring key competencies to execute. Figure 4 highlights the *Energy Optimization* activities currently the focus of the Integrated Design Process Model for High Performance Buildings (IDPM^{HP}). The *define phase* consists of assembling the high performance team and the identification of constraints, footprint options, and goals. The *design phase* consists of design optimization simulation, evaluation and integration of system relationships, informing of results, fine tuning of design, and verification simulation. The *documentation phase* includes the process of integrated design and detailing, (described in section 5 of this paper) and coordination and production documentation.

Early case studies used to test the IDPM^{HP} have found the most critical feature of the design process to be an early and accurate definition phase that is highly inclusive of team members and disciplines (Magent et al. 2005). The most common problems found on early case study projects are the lack of energy strategy tools utilized early in the design optimization process, a lack of defined tolerances and prerequisites for design decisions, late changes to designs that threaten perform-

FIGURE 4. Level II BDPM^{HP}: Energy Optimization Process.



ance, and a lack of constructability knowledge and competencies during design development and detailed design. The results of this research phase will directly inform owners seeking to form high performance building teams, as well as design and construction organizations. This research will also advance existing models of the engineering design process that do not currently capture the essence of design as a network of design actions made up of commitment-producing decisions, and data-producing analyses.

4. Continuous Value Enhancement Process

Research Goal Efforts to improve the delivery of high performance building projects have focused heavily on the capabilities of design professionals and the design process. While designers have the greatest influence over systems level issues (i.e., building envelope, mechanical/ electrical systems, day lighting), construction professionals and owners have valuable knowledge that can significantly improve other aspects of sustainability such as material choices, indoor air quality and waste avoidance strategies (Riley et al. 2004). Yet, very few processes exist to actively extract ideas from these resources and thus numerous opportunities to impact the delivery of high performance facilities are missed.

This research aimed to define a process that systematically evaluates pertinent ideas from owners and construction professionals to improve the efficiency and cost effectiveness of achieving more sustainable buildings (Pulaski 2005). By integrating environmental objectives into current practices for managing constructability knowledge, the Continuous Value Enhancement Process (CVEP) was created (Pulaski and Horman 2005). CVEP provides a simple yet rigorously tested method to advance sustainability objectives and high performance building practices throughout the design and construction process.

Key Findings The process was implemented on three projects at the Pentagon renovation project. CVEP implementation over a 6 month period resulted in 57 ideas, 38 of which represented more sustainable solutions that also improved constructability (Pulaski 2005). Over $19 million of potential and actual first cost savings were reported, as well as significant benefits to the reduction of resources consumed, reduced life cycle cost, improved maintainability and health and safety (Pulaski 2005). This is significant as these ideas are likely to never have been implemented without CVEP. Examples include efforts to salvage materials and equipment for reuse, eliminate unnecessary requirements and over-engineering and the selection of more sustainable products such as carpet tile, wheat straw board and pre-finished drywall partitions. Each example produces a profile, such as the one in Figure 5. This profile is generated from the project

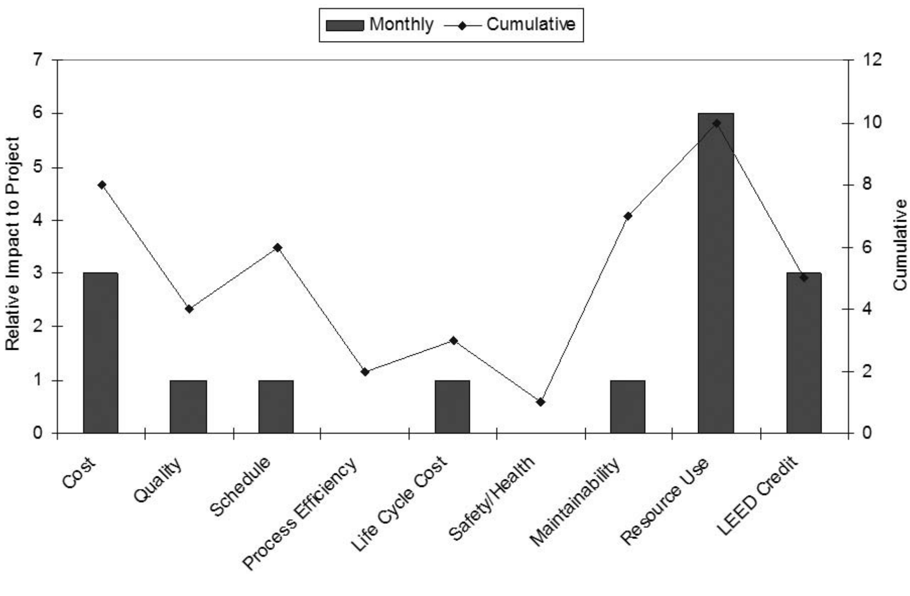


FIGURE 5. Sample CVEP metric from the Pentagon project.

team's evaluation of the idea on each of the variables shown on the x-axis. By reviewing the shape of the bar groups under each of constructability and sustainability, this figure enables an evaluation of how well the team is balancing their emphasis on constructability and sustainability when they propose improvements. In terms of the research, the next step is to test the external applicability of CVEP by implementing it on an upcoming smaller scale project unrelated to the Pentagon renovation.

The research findings reveal that owners and construction professionals have significantly value added knowledge and capabilities that can streamline project processes while advancing sustainability objectives (Pulaski and Horman 2005). Extensive implementation and evaluation on multiple projects of variable scales, including those of the Pentagon renovation, demonstrates that CVEP is a simple, yet rigorous process for project teams to systematically generate and evaluate innovative ideas and improve the delivery high performance building projects.

5. Integrated Design and Detailing

Research Goal A significant source of waste in current building design and construction projects is the documentation of design information. Design drawings are created by specialty consultants for multiple audiences and at variable levels of detail. The duplication, redundancy, and lack of coordination of documents makes them costly to produce and prone to errors. As a result, valuable funding that could be spent on higher quality building materials and technical systems is wasted. The concept of integrated design and detailing has been developed to describe efforts in which technical engineering skills, construction experience, and maintenance and repair knowledge are applied concurrently in the development of design documents. The lean and green research thrust in integrated design and detailing is an effort to explore how lean construction principles that maximize fabrication and production processes can be applied to streamline the design documentation process. The immediate focus of this thrust is in the area of mechanical system design, engineering, and construction. The goal of this research is to demonstrate that integrated design and detailing practices not only reduce first costs of mechanical systems, but also improve the operating efficiency of these systems.

Key Findings The early phases of this research have been completed and involve a detailed analysis of the design and documentation processes employed by design-build mechanical contractors (Riley et al. 2005). The criteria used to identify the value of integrated design and detailing processes were as follows: 1.) *Lean processes*—activities that streamline construction process, improve clarity of design, improve the integration of the mechanical design process with other systems, reduce potential for error in design or construction, and/or increase the shop portion of fabrication; and 2.) *Green results*—produces savings in first costs, energy, water, or material requirements of system, adds to flexibility of system, reduces long-term maintenance costs, and increases the use of more environmentally friendly materials.

Through this effort, a set of integrated design and detailing competencies have been identified with examples in which both first cost savings and operating efficiency improvements have been achieved on case study projects (Riley et al. 2005). Examples of these competencies include the: 1.) the ability to implement innovative "right sized" mechanical systems that require high levels of integration and communication between engineering and field operations; 2.) the optimization of equipment layouts and piping/ductwork configurations that reduce the size and scope of wet side (piping) and dry side (ductwork) distribution systems; 3.) the development of highly coordinated schematics and scaled engineering drawings that facilitate accurate bidding of other trades and reduce field generated change orders; and 4.) constructability and value engineering suggestions that allow the adaptive re-use of mechanical system components on retrofit projects. In several cases that are described more thoroughly in Riley et. al (2005), when asked to re-design mechanical systems produced with conventional methods, integrated design and detailing efforts of mechanical contractors produced 20% reductions in mechanical system costs coupled with 20% improvements in energy efficiency. These powerful results translate directly in to cost savings that can be directed to cover the added expense of green building systems, while at the same time, increasing the LEED Energy credits and resulting in long term savings in energy costs.

6. Production Metrics for High Performance Building

Research Goal Savings in construction costs through improved production and productivity are critical on green building projects, as they can be used to offset the costs of high performance building components. Lean manufacturers often make use of prefabricated systems because they offer many advantages to production and productivity improvement, as well as quality and schedule control. This research examines the effects of how an expanded use of prefabricated systems can contribute or detract from green building goals. Specifically, it assesses in detail the tensions that exist between the construction of green buildings fabricated on site and factory prefabricated environments. Sustainable practices are evaluated in broad terms including economic, environmental, and social implications. The goal of this research is to help define parameters that evaluate the contribution and limitation of prefabrication strategies by defining the costs and benefits metrics of such systems.

Lean principles help streamline production of systems and reduce waste, and have been shown to be highly applicable in building construction. The lack of repetition that exists in building designs, however, often limits the application of lean principles. A key tenet of lean construction is the expanded use of prefabrication due to the production advantages of prefabrication environments (Pasquire et al. 2004). The choice of using prefabricated systems versus site-built building systems must be made carefully and is typically based on a broad set of regionally specific economic issues. With additional considerations made for environmental and social factors, this choice becomes even more complex.

While an increased use of prefabrication and the associated lean principles that apply have a strong bearing on production issues, additional metrics for evaluating building systems choices are needed to show how *lean* production principles can be applied to achieve *green* results. In particular, a key objective of this research is to develop a decision model to guide choices and strategically adopt prefabrication and engineered systems in the design and construction planning of green facilities.

Key Findings The evaluation of prefabricated systems in economic terms is highly influenced by local labor costs (Luo et al. 2005). Significant additional benefits exist however, to the use of prefabricated systems in green buildings. An evaluation of prefabricated systems through the use of lean principles and green performance properties helps to identify both the narrow and broad impacts of prefabricated systems in green construction. Table 2 illustrates a qualitative assessment of the factors influencing the decision to prefabricate or to fabricate on site. Economic, environmental, and social factors are included in this comparison. Future research in this area will focus upon a more rigorous taxonomy of production methods based not only on labor efficiency, but also on factors critical on green building projects.

7. Scalable Characteristics of High Performance Delivery

Research Goal The pre-design process of a construction project sets the foundation for all subsequent phases. The added complexity often experienced on high performance projects heightens the criticality of the pre-design process. There is much ambiguity within the construction industry as to the actions that are necessary for the success of a high performance building project. For example, building owners might be led to think that a sustainability consultant involved early in a project would be the best way to pursue high performance project goals. Yet, recent research by GSA (2004) is showing that an integrated team with past experience in green projects will lead to superior outcomes. Research is needed to peel away the current ambiguity involved in high performance project delivery by pinpointing and understanding the practices that are fundamental to these building projects. To this end, this research program will determine the scalability of key success factors used in the pre-design phases of high performance building projects in order to identify the fundamental characteristics of high performance building delivery.

TABLE 2. Evaluation of economic, environmental, and social aspects of prefabricated versus site-built systems.

Decision Factors	Prefabrication	Site-Built
Economic Issues		
Quality	More reliable quality can be achieved in a shorter amount of time (especially for large-scale projects)	Less reliable (depending on the site conditions and the skill level of the labor)
Component and material supply chain	Long term supply chains for materials can be established	Supplies restricted to project-based purchases
Schedule Length and Reliability	Longer lead time, but reduced erection time and more reliable duration	Shorter lead time, but longer construction schedule and less reliable duration
Coordination Time	Extra coordination needed between the site and the plant	More time for coordination and opportunities to adjust dimensions
Flexibility	Changes often cannot easily be made in the field	Limited adjustments can be easily made in the field
Impact of Changing Orders	May cause delay & extra costs: less controllable situation for large-scale projects	May cause delay and extra costs: often can be better accommodated
Delivery and Shipping	Varies depending on the locations of the prefab. plant and the material supplier	Shipping fee needed for raw material delivery only
Maintenance Costs	Improved quality can lead to reduced maintenance and operations costs	Defects due to site conditions can lead to higher maintenance and operations costs
Environmental Issues		
Quality	Improved quality can lead to improved performance	Site defects can reduce performance
Material choices	A greater variety of specialty materials can be used due to more developed supply chains	Material choices are limited to sporadic availability, and capabilities of on-site labor
Material Waste	Less waste due to use of larger raw material lots	More waste onsite; extensive packaging for delivery
Transportation Energy	More gas consumption	Less gas consumption
Flexibility	Modular systems can be reconfigured more easily	Minor onsite variations (dimensions, etc.) can be easily accommodated
Deconstruction	More likely to be easily disassembled for reuse or recycling	Disassembly and separation is usually more costly
Social Issues		
Local Labor	Less local labor needed	Can employ local labor to fabricate and install components onsite
Working conditions	Improved working conditions and more stable job market	Variable working conditions and more sporadic job market
Skill level	Craft and technical skills needed	Craft and problem solving skills are elevated

Scalability refers to a property of having equal application to large and small ventures. It is used in this research to determine whether particular actions apply to both large and small high performance building projects. For example, if energy modeling can be shown to have equivalent applicability to large and small scale projects, this practice can be said to be scalable and therefore possess properties fundamental to high performance building project delivery. Fundamental principles should be applicable on projects of different scale, and so the fundamentality of a principle can be evaluated by assessing its scalability.

Key Findings The product is expected to be a set of guidelines that will enable those involved on the pre-design team to peel away the current ambiguity involved in high performance projects, and hence add heightened value to the pre-design process (Harding 2005). These fundamental and scalable principles will provide a guide to successfully delivering a high performance green building of any scale.

A case study will be conducted to map the pre-design process of successful high performance building projects. This template will list high performance building principles at each critical point of the pre-design process. Hypotheses will be generated and tested by applying the template to projects of different scale.

8. Field Guide for Sustainable Construction

Research Goal Recognizing the potential impact that construction has on the success of high performance projects, a field guide for workers was developed to improve the capabilities of workers on green projects. Based on real project experiences and case study examples, this field guide was designed to provide targeted advice to workers to raise their awareness of sustainable practices in order to help them achieve green objectives.

Key Findings Developed for the renovation of the Pentagon, the field guide was compiled by a Penn State graduate class. Structured for use in the field, the guide can be utilized by project engineers tasked with, say procurement of materials throughout the project. Alternately, trade contractors would also use the field guide for ideas about how to best contribute to the sustainable goals in their area of the project. Case study projects are used extensively to promote learning amongst field workers (Pulaski et al. 2004).

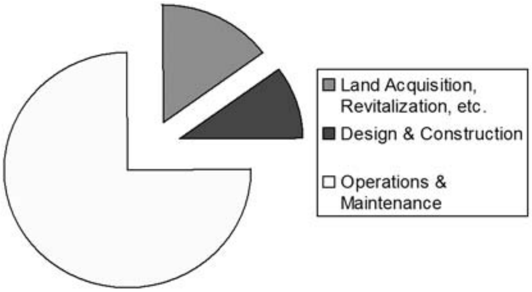
During the summer of 2004, the field guide was piloted with key trades on Wedge 2 of the Pentagon renovation. The aim of the implementation study was to identify whether field workers found the information usefully formatted and to evaluate the impact of the field guide at raising awareness about sustainable construction issues. Three focus sessions were used to collect insight and feedback on the field guide. All subjects approved of the format of the field guide with few exceptions.

The most crucial insight achieved by implementing the field guide has been that education at the field level is key to impacting worker behavior. Mirroring the cultural changes concerning safe work practices in this industry, raising the awareness of workers to what helps and harms sustainable project goals results in progressive changes to worker behavior. Although assessed over a short period workers introduced to the field guide felt they knew more about sustainable issues and were more inclined to adopt sustainable practices (Dahl and Horman 2004). The challenge is that the impact of this raised awareness is often difficult to tangibly measure. Yet, similar to the experiences of raised safety awareness, trend improvements at the industry level are key. For instance, insurance companies measure histories of accident rates and worker time lost over multiple projects to set a company's insurance premiums. Future implementations of the field guide are planned for worker accreditation/ site orientation in order to maximize the impact that awareness of sustainable field practices has on building project sustainability.

9. Integrating Operations and Maintenance Knowledge in Design

Research Goal Building operation and use is one of the most critical aspects of high performance buildings, but operation and maintenance (O&M) information is often not communicated effectively to the design and construction team. "Operating expenses represent over 95 percent of building life cycle costs, yet operations and maintenance personnel are usually the last to be consulted during programming

FIGURE 6. Total cost of facility ownership. Source: U.S. Federal Facilities Council (2001).



and design" (National Institute of Building Science 2003). The Federal Facilities Council (2001) found a similar magnitude of total building expense in operations (see Figure 6). The lack of effective communication often results in inefficient O&M procedures, additional O&M staff requirements, increased energy consumption, and reduced occupant comfort. The consequence is a facility with increased operating costs that is not conducive to the health of the environment.

Little is known about the most effective timing and approaches to provide O&M input in project design and construction. This research project focuses on the optimal injection of O&M information in the project delivery process to address this critical concern. In particular, it will examine innovative project delivery processes that improve the role of facility management in the early development stages of projects, where a high level of influence can be attained by O&M personnel.

Key Findings Research has shown that when just one percent of a project's first costs are spent, up to 70 percent of the life-cycle costs of the project may already be committed (Romm 1994). This project will identify the most effective methods to inject O&M information in design and construction.

Preliminary research has begun to investigate the use of Design-Build-Operate-Maintain (DBOM), an innovative delivery method that integrates the designers, the contractors, the operations and maintenance staff under one contract to the owner (Doran et al. 2000; Smith and Castellana 2004). DBOM can be used as a delivery process for a project to optimize the input of O&M knowledge in the project. By contracting the project team to operate and maintain the facility for a period of time after construction, the project team is incentivized by the delivery method to design and construct an efficient building. As the building performs more efficiently, energy costs are likely to decrease as this directly affects profitability for the contracted DBOM team.

The research will also evaluate other important requirements to effectively inject O&M knowledge into the design and construction process. One critical waste-inducing practice adopted by owners is the separation of capital development and O&M budgets. Working with key owners, new policies are being proposed and experimentally implemented under this research initiative.

INTEGRATION STRATEGY: LEARNING BY DOING

The approach taken by the Lean and Green Initiative on specific focus areas through the plan, manage, design, construct operate life cycles is integrated through the application of each research thrust within the context of actual green building construction projects. These projects, planned and organized through the American Indian Housing Initiative (AIHI) at Penn State, offer graduate students an opportunity to weave their research goals and collect data from projects that they also help to plan, design, and construct. For example in the current project, CVEP was used by the AIHI class designing the facility to evaluate sustainable material alternatives. The class learned a new decision-making tool, and also enabled the research to be critically extended by showing the applicability of the CVEP tool on this project.

A partnership between Penn State and Chief Dull Knife College, AIHI is a research and education program focused on the adoption and deployment of sustainable technologies to address the housing crisis facing American Indians. Each year, through the work of research and coursework, a green building is designed and built on an American Indian reservation. Since it inception in 1998, AIHI has constructed four homes and three community facilities on three reservation in the northern plains of the US. In the last fours years, all the efforts of AIHI have been focused on the Northern Cheyenne reservation in Montana. In the summer of 2005, AIHI partners will construct a 4000 SF daycare and early childhood learning center on the Northern Cheyenne Reservation that will pursue a LEED Gold Certification.

All AIHI projects are constructed during a two to three week blitz build in which student teams, volunteers, and tribal members converge to construct a project using sustainable building materials and methods. Table 3 illustrates the typical two week sequence of an AIHI project using the construction of the 2003 Sustainable Technology Center project as an example. This facility included load-bearing strawbale construction, and the adaptive re-use of an existing building foundation and steel frame. Cost

TABLE 3. Construction sequence of 2004 AIHI project: a sustainable technology center on the campus of Chief Dull Knife College on the Northern Cheyenne reservation.

Project Start
This project began with the evaluation of an existing quonset hut for potential refurbishment and reuse. The results of this analysis found the structural frame and foundation to be suitable for a new building. The remaining elements of the structure were disassembled and recycled prior to the arrival of the on-site team. A new slab-on-grad was then poured including embedded heating tubes.

Prefabrication
Student teams met on site to preview the project plan with volunteer participants and tribal members. On days 1-3 mid-span trusses, window boxes and headers were prefabricated on the ground and painted with highly reflective low VOC paint. The team also conducted workshops on straw wall construction, and prefabricated necessary reinforcing rods and pins.

Structural Frame Construction
Load-bearing strawbale walls were assembled using six 16″ courses of 48″ long by 18″ deep bales. Box beam and header materials were lifted on top of the bales, and structural insulated panels (SIP) panels were lifted into place by hand to form the roof. Site-built glazing panels were then assembled out of light wood frames and Polygow (polycarbonate) panels.

Interior Finishes
Framing of limited interior walls was completed along with 3 coats of cement stucco. Windows were installed and reflective window sill panels were installed. Strawboard was cut and fit as a sheeting material in place of drywall. SIP panels were painted with a highly reflective and fire retardant paint. The structural frame was painted, and the site was cleaned.

Final Finishes
Metal roof and cement board sheathing were applied to complete the base building. Local contractors installed plumbing, electrical systems, commercial overhead doors, and final finishes. The completed building will house a construction lab and teaching kitchen which are currently being installed. The facility will also be used to facilitate future AIHI projects.

and production data were also collected on this project which will serve to inform future community-built projects planned by AIHI.

Table 4 summarizes the techniques in which Lean and Green research thrusts are currently applied on AIHI projects. For each research area, a specific activity and analysis is performed and incorporated into AIHI project processes.

The opportunity to observe, assess, and even influence an actual project provides the Lean and Green research team a unique environment in which to conduct research. Free from the constraints of contractual obligations, the functions of design and construction on AIHI projects take place outside the confines of traditional project limitations, permitting level of integration not typically found on building projects. At the same time, the constraints placed on students and research teams by the actual project conditions demand practical and pragmatic solutions to design and construction issues. The blend of a fully integrated team environment combined with the constraints of an applied research program contributes directly to the development of practical and useful research results.

TABLE 4. Integration and application of lean and green research thrusts on AIHI projects.

Research Thrust	Research Activity	Impact on AIHI Project
1. Facility Procurement Process	Identify relationships between value and long term facility costs to an owner	Help facilitate life cycle analysis and decisions during the planning phases of projects.
2. Enabling Delivery Strategies	Track roles and timing needed for disciplines and competencies of project	Strengthen interaction between design and construction expertise, and enables design for production approach
3. Integrated Design Process Model	Mapping of constraint and contract free design and environment	Improved utilization of analysis tools and techniques required for high-performance facility design
4. Continuous Value Enhancement Process	Implement CVEP process for the identification and evaluation of improvement ideas on AIHI projects, specifically the use of alternative materials	Ideas for alternative material are evaluated systematically and in consideration of weighted project conditions
5. Integrated Design and Detailing	Value of detailed design and engineering drawings generated with construction competencies is evaluated	Details design and production drawings that simplify and streamline construction are utilized on site by multiple audiences
6. Production Metrics	A blend of prefabrication and site-built techniques are planned and evaluated on blitz builds	Detailed evaluations and design of productive work environments needed on blitz-build projects
7. Scalability of Sustainable Design	Assess integrated design process on small scale projects	Facilitates use of advanced processes developed on large scale projects to be implemented
8. Field Guide for Sustainable Construction	Track trade-level actions, competencies, and training needed for on-site management of sustainable construction projects	Increased awareness of material handling, waste management, and construction sequencing requirements needed to achieve green goals
9. Operations and Maintenance Knowledge	Track considerations for the skills and demand on O&M staff during design of systems and controls	Emphasis on low-maintenance and easily maintained and controlled building features

CONCLUSIONS & RECOMMENDATIONS

High performance "green" or "sustainable" buildings are an important new breed of building able to balance short and long term goals for the built environment. As strategies and technologies are developed for these buildings, research is needed on the competencies and processes used to deliver these projects. Such research promises to maximize potential levels of sustainable performance *and* improve the cost effectiveness of these important facilities.

This paper defined an emerging research and education program at Penn State focused on understanding the delivery of high performance projects. The program is underpinned by theory that reduced process waste directly relates to levels of sustainability as well as to the business case of a development. Through the Lean and Green Initiative, value-adding and waste-reducing strategies are being applied to the capital project delivery process throughout the life cycle of planning, managing, design, construction, and operation. Focused efforts throughout this lifecycle target areas of improvement that are critical to the delivery of high performance buildings. This paper highlighted these efforts revealing the potential benefit of delivery-oriented research to the goals and impact of high performance buildings in this industry. Continuing research and education are needed to capitalize on this emerging area.

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