LEAN PRINCIPLES FOR PREFABRICATION IN GREEN DESIGN-BUILD (GDB) PROJECTS

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ABSTRACT

Savings in construction costs through improved production and productivity can be critical on green building projects, as they can be used to offset the costs of high performance building components. Prefabrication of building components is often used by contractors to reduce costs. If employed effectively, prefabrication can enable process standardization, shorten lead times, improve quality control, and reduce material waste. Several tools have been developed to help select prefabrication strategies and most of them focus on design-bid-build project environments.

This paper explores how benefits achieved in lean approaches to prefabrication can impact green project goals. More specifically, the paper examines the effects of how an expanded use of on-site/off-site prefabricated systems can contribute or detract from green building goals through evaluating the interplay between multiple economic, environmental, and social variables. Building on previous research that has developed tools for guiding the adoption of prefabrication practices, the design of new metrics for lean and green construction will be developed and presented to provide selection guidance for the use of prefabrication on green building projects in design-build environments.

KEY WORDS

Prefabrication, Sustainability, Green building.

INTRODUCTION

"Prefabrication is all things to all men, and a source of confusion to many." (Bruce and Sandbank, 1972) People said so several decades ago, which somehow revealed the complexity of the utilization of prefabricated systems because they generally rely to a varying extent upon lots of social and economic factors, such as building labor and the industries which supply building components. The situation turns to be even more complicated, however, when green building becomes a critical need of the market and environmental factors start to play an important role as well. How to balance the pros and cons of different prefabrication methods (e.g. onsite/offsite prefabrication, preassembly, and modularization) in buildings with green goals thus becomes a growing concern among many project teams.

The paper presents the findings from an ongoing research at the Pennsylvania State University. It identifies the lean features and green potentials of prefabrication, especially the possible interactions between these two, and intends to explore the actions design-builders may take to maximize the value of prefabrication in Green Design-Build (GDB) buildings.

BACKGROUND

Earlier literature indicated that the application of prefabrication in America could be traced back to almost 130 years ago when the wooden frame house was developed. People used machine-cut nails to replace hand-forged nails or wooden pegs in construction, and the standardized wood production started soon after the power saw was brought in. All these little movements became

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part of "the first elements of prescheduled procedure upon which modern mass production was based." (Bruce and Sandbank, 1972) It was later, however, during the depression in the early 20th century and then in wartime that prefabrication gained its initial serious attention from the US housing market, because the modern E&C industry suddenly realized that prefabrication suited the market perfectly as a means of saving labor and providing temporary or low cost accommodation rapidly. Lots of other benefits (e.g. lean features) of prefabrication have been explored since then through extensive practice and research. It is now widely spread to various industry sectors and no longer merely a strategy for cheap housing.

CHANGES IN CRITICAL EXTERNAL FACTORS

To better understand the evolvement of prefabrication and how that relates to the changes from the external environments, examining some of the key factors can be very instructive:

- **Labor**: The changes in labor make prefabrication a more favorable option nowadays. Labor cost keeps going up. According to statistics compiled by Bureau of Labor Statistics (BLS), the employment cost (total compensation) in the construction industry increased by two times from 1985 to 2004, whereas for the manufacturing industry the figure almost jumped by three times from 1980 to 2004.
  It should also be noted that the available skilled craftworkers such as terrazzo workers, electricians, sheet metal workers, and HVAC mechanics tend to decrease while their employment demands are expected to continually grow faster than the industry average. (BLS website)
- **Market Trends**: Clients now have higher expectation of every aspect of their final products (i.e. quality, variety, cost, as well as completion time). "Maximize value and minimize waste". That is why lean production finally won the market and took place of mass production. One of the downsides in prefabrication people would typically think of is the possible inhibition of design creativity due to the large amount of repetitive/standardized design. However, standardization is only ancillary to prefabrication, not a 'must' function. If employed appropriately, prefabrication can still enable variety and minimize cost at the same time (e.g. prefabricated wall panels with different finishes)
- **Technologies**: Advances in technologies (e.g. computer-aided design / visualization tools, decision support software, automated manufacturing facilities, etc.) provide lots of opportunities in innovation/improvement of design and building methods. They also allow for easy information transfer and supply chain management. Potential technical cooperation between different parties can be further explored if necessary.
- **Green/Sustainability Values**: Eliminating the "concept of waste" and creating a healthier environment through design and management has become another big goal of the nation in recent years. Energy efficient building materials/systems with lower environmental impact are getting prevailing in the market. People start to concern about things such as IAQ (Indoor Air Quality), LLC (Life Cycle Cost), the Four R's (Reduce, Reuse, Recycle, and Regulate), etc. Related regulations, policies, rating systems, and cost-benefit evaluation tools have been developed accordingly. Although prefabricated systems are often used as means of reducing project costs, their potential green benefits are hard to ignore. Researchers in Australia suggested that the 'green' performance of prefabricated building systems be measured through embodied energy and sustainability assessment criteria ten years ago (Outhred and Graham, 1995), which to a certain extent clarified some of the synergies between prefabrication and green construction.
- **Project Delivery Systems**: Design-bid-build, design-build, and CM at risk are the three major project delivery systems in the US currently, with design-build being the fastest growing method during the past twenty years. According to statistics compiled by the Design-Build Institute of America (DBIA), from 1985 to 2005 the market penetration of design-build delivery system increased by 8 times, with "traditional" design-bid-build serving 50% of the market and design-build 40% in 2005. The predicted results further indicate that by the year of 2015, those figures could be nicely reversed (the Design-Build Institute of America website). How to maximize the value of prefabricated systems in design-build projects therefore becomes a new research problem.

PREFABRICATION AND LEAN

Derived from the Toyota Production System, lean principles were initially developed in post-World War II Japan at the Toyota Motor Company. These principles are focused at the process, project and enterprise or organization level and have

Table 1: Contribution of Prefabrication Strategies to Lean Principles

Domain Area	Lean Principle	Amplified by Prefabrication	
		yes	no
Customer Focus	Meet the requirement of the customer either through improved timing, quality, or cost	✓❑	
	Define value from the viewpoint of the customer (project)	✓	❑
	Use flexible resources and adaptive planning to respond to changing needs and opportunities	❑	✓
	Cross train crew members to provide flexibility	❑	✓
	Use target costing and value engineering	✓	❑
Culture/People	Provide training at every level	✓❑	
	Encourage employee empowerment	✓❑	
	Ensure management commitment	✓	❑
	Work with subcontractors and suppliers to regularize processes and supply chains	✓❑	
Workplace Organization/ Standardization	Encourage workplace organization and use of the 5S's	✓❑	
	Implement error-proofing devices	✓❑	
	Provide visual management devices	✓❑	
	Create defined work processes for repetitive tasks	✓❑	
	Create logistic, material movement and storage plans that adapt to changes in workplace configuration	✓	
Waste Elimination Part I (Process Optimization)	Minimize double handling and worker and equipment movement	✓	
	Balance crews, synchronize flows	✓❑	
	Remove material constraints, use kitting, reducing input variation	✓❑	
	Reduce difficult setups and changeovers	✓❑	
	Reduce scrap	✓❑	
	Use TPM (Total Productive Maintenance)	✓❑	
Waste Elimination Part II (Supply Chain)	Institute JIT delivery, supply chain management	✓❑	
Waste Elimination Part III (Production Scheduling)	Use production planning and detailed crew instructions, predictable task times	✓❑	
	Implement last planner/reliable production scheduling/short interval production scheduling	✓❑	
	Practice last responsible moment/pull scheduling	❑	✓
	Use small batch sizes, minimize WIP	✓❑	
	Use decoupling linkages, understand buffer size and location	✓❑	
Waste Elimination, Part IV (Product Optimization)	Reduce parts count, use standardized parts	✓❑	
	Use pre-assembly and prefabrication	✓❑	
	Use preproduction engineering and constructability analysis	✓❑	
Continuous Improvement and Built-In Quality	Prepare for organizational learning and root cause analysis	✓❑	
	Develop and use metrics to measure performance; use stretch targets	✓❑	
	Create a standard response to defects	✓❑	
	Encourage employees to develop a sense of responsibility for quality	✓❑	

helped the US manufacturing industry make significant progress over the past three decades in increasing productivity and product quality while lowering product lead times and costs. The similarities and interdependence between the manufacturing industry and the construction industry indicate the great potential of applying lean principles to construction. Table 1 below articulates how prefabrication strategies can contribute broadly to the lean principles for construction defined by the Construction Industry Institute (CII, 2004).About This Research: Why Green Design Build (GDB)?

The three main reasons that GDB buildings are chosen as the specific target group in this research are as follows:

- GDB is a very promising field to explore for the future of our building industry due to its potential combined social, economic, and environmental benefits from green building and the design-build project delivery method which have both gained momentum in recent years. The U.S. Environmental Protection Agency (USEPA) defines green building as 'the practice of creating healthier and more resource-efficient models of construction, renovation, operation, maintenance, and demolition.'(USEPA website), from which it should be noted that the term 'green building' covers not only the 'green attributes' of the final building products but also the construction process itself (e.g. health and safety, energy savings during construction, etc.). However, most existing guidance or rating systems for green buildings are more from the owner's, user's, and/or designer's perspectives; therefore their interests, such as energy efficient systems and IAQ, are often highlighted. By working as a team, design-builders are at a better position to address the needs from every team member.
- The related research and practice on GDB buildings remain limited at present in the U.S. This may be largely due to the fact that lots of green technologies and criteria are still new to many design-builders and few practical cost- & benefit-evaluation tools are available to facilitate their decision-making process. The unknowns can possibly lead to multilevel coordination gaps between members on the supply chain and cause substantial cost/time overruns at the end.
- Currently, there are no such decision-making frameworks for prefabrication that can explicitly address the needs of GDB projects. Considering the large amount of planning and coordination needed regarding prefabrication in a project both before and during its construction, it is now commonly accepted that a project-wide strategy should be developed at an early stage to achieve the maximum benefits from prefabrication. Most existing tools contain a preliminary decision guild followed by a quantitative analysis. The first part is based on the very basic project information such as schedule, site attributes, availability of local labor and suppliers, etc, whereas the latter part usually asks for more specific details (e.g. material cost, labor cost, equipment type, etc.) to optimize the accuracy of its results. These tools, while useful in many traditional design-bid-build projects, only include very few 'green' factors (e.g. safety & health issues) for consideration, which makes them less circumspect and pertinent on green projects. Furthermore, for design-build projects, detailed information is typically unavailable at an early stage due to their nature. Undefined or poorly-defined design details can make it difficult to utilize these tools and even mislead the final solution.

CASE STUDY EXAMPLES

Three illustrative case study examples are provided to illustrate how the use of prefabrication strategies can directly address green goals on building projects.

EXAMPLE 1: REDUCING WASTE AND IMPROVING QUALITY IN PIPE FIXTURES

A common strategy employed by plumbing and mechanical contractors is the prefabrication of pipe spools and manifolds to reduce field labor and permit construction in a factory environment. This strategy has obvious benefits to building green through (1) reducing material waste as longer sections of pipe can be used in the factory and the probability of using scrap is increased, (2) reducing the hazard and pollution caused by welding and sweating pipes on site, (3) centralizing recycling efforts at the shop, (4) improving quality through reduced leakages and maintenance that can potentially lead to IAQ problems. In addition, the improvements in cost and schedule through prefabrication can allow management and funding resources to be directed towards other green features of projects that require cost premiums.

EXAMPLE 2: SUPPLY CHAIN OF GREEN MATERIALS

A significant challenge on green projects is the use of new and unfamiliar materials. Modularization of homes and buildings is an expanding and emerging market. In addition to the benefits of prefabrication provided in the piping example, large scale modularization and prefabrication efforts can help produce reliable supply chains of new and emerging green materials. In one case observed, a company seeking to acquire LEED ratings of factory-built modules developed relationships with the manufacturers of environmentally friendly materials such as wheat board. This allowed the vendor to customize the material to be ready for the production line, and to meet the needs of the prefabrication process.

EXAMPLE 3: DESIGN FOR DISASSEMBLY - IN THE AUTOMOTIVE INDUSTRY

A growing value in the green building industry is the concept of design for disassembly, however many building owners are reluctant to invest in this strategy due to the notion that it would not pay off until the building is decommissioned. The automotive industry can again be used to demonstrate a valuable lean and green synergy. The growing concern for increasingly limited space of waste disposal, legislation on End-of-Life Vehicles (ELV) has been getting stricter in Europe and other regions, which calls for improved recyclablility of car components. Many new design concepts have been developed such as '*Design for Environment*', '*Design for Recycling*', and '*Design for Disassembly*'. Removing a wiring harness at the end of a car's life is typically very time consuming and costly since it's always covered by other car parts which have to be destroyed earlier such as plastic bolts, strips, guides, and other types of fasteners. An alternative fastening system was designed at Delphi Automotive Systems to facilitate both disassembly and assembly. The designers simply replaced the textile or plastic tape by a self-adhesive hook or loop type tape, with the loop type tape covering the harness and the hook type tape determining the routing. In this way, the harness can be easily assembled and quickly removed just by pulling at one end. Several other advantages were discovered in a following technical feasibility study, such as maintained mechanical performance, improved noise behavior and fastening properties, simplified production process, etc. A rough cost evaluation for a high volume car line indicated that a total annual cost saving of about $8 million could be achieved for the product itself, production, assembly and service (Diegmann, et al. 2002). This example demonstrates how efforts to consider disassembly and recycling during design can actually yield first-cost savings in production in addition to life cycle maintenance and repair.

SUSTAINABILITY AND PREFABRICATION

To begin the development of taxonomy of prefabrication and site-built strategies and their impact on green building objectives, improved definitions of the relationships between the two are needed. Table 2 illustrates a qualitative assessment of the factors influencing the decision to prefabricate or to fabricate on site. The broader definition sustainability and the "triple bottom line" (economic, environmental, and social factors) are included in this comparison.

SYNERGIES BETWEEN PREFABRICATION AND SUSTAINABLE OBJECTIVES

The examples above help to illustrate the need to develop taxonomy of prefabrication benefits and outcomes that help contribute to green goals. This would allow the adoption of these strategies for broader issues than cost savings, and help articulate the value of designing for prefabrication on design-build projects. To articulate the synergies between prefabrication and sustainability and provide focus to this research, four main categories of sustainable objectives in green building construction are listed and defined below (Pulaski, 2005).

Life Cycle Cost: The total-cost-of-ownership involved in acquiring, installing, starting up, personnel training, operating, maintaining, and disposing of products/ materials/ systems over the various service lives.

Safety/Health: Safety of construction/ facility workers and/or health of building occupants, including indoor air quality.

Non-Renewable Resources: Reduced use of energy, fuel, water, and/or increased use of renewable/recyclable materials during construction and/or operation.

Material Waste: Reduced material waste during construction

Seven key attributes of prefabrication that support sustainable objectives are identified in Table 3 and expanded below:

1. **Increased potential of supply-chain integration to support sustainable goals:** The successful use of prefabrication requires all those involved at the different stages of the project to spend considerable time planning the details and sequences. Such integration is also very beneficial in green building construction. Inno-

Table 2: Evaluation of economic, environmental, and social aspects of prefabricated versus site-built systems. (Adopted from Horman et.al, 2005)

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

vative green techniques, designs, products, or specialized tools can be introduced, evaluated, and implemented among the designer, builder, fabricators and suppliers of green materials more efficiently.

2. **Safer working conditions**: Previous research indicates that the situation of working environment does have a big impact on productivity. By cutting down the onsite work, prefabrication reduces the exposure of workers to heights, weather and hazardous operations so as to provide safer and more reliable working spaces (e.g. reduction of hot works such as welding, cutting, and brazing which may bring fire risk during construction). Risks caused by interference with other ongoing construction activities are alleviated or removed as well. In addition, the fact that many building units are prefabricated at grade level, tested and then precommissioned before being delivered can also result in fewer safety restrictions and reduced supervision onsite.

3. **Reduced environmental impact:** A project using substantial prefabrication features a less congested site with fewer site workers, machines, stacked materials, temporary structures and onsite activities. All these facts can be translated into lots of environmental benefits to both the project itself and local communities, such as less noise, dust, air pollution, material waste, and energy use. Although it's been argued for a while that prefabrication may increase the transportation cost, many cases do show that with a thoughtful plan on material sizing, packaging and delivering, prefabrication typically consumes less energy in transportation and onsite works.
4. **Economic impact in local communities:** Relocation of work offsite potentially reduces economic impacts upon the local communities by reducing influxes of construction workers, or conversely, reduced prefabrication and increased on-site construction can help to provide jobs in the community where a project is being built.
5. **Easier recycling of materials and supplies in an off-site environment:** Better control in factory environment allows for easier material handling and recycling. It also removes the need of extra time/cost/personnel for transportation and onsite waste management.
6. **Enhanced flexibility and adaptability** Prefabricated units such as pre-cast concrete wall panels and complex MEP assemblies can be designed to be easily reused or relocated. The fact that the building, facility or structure is assembled from prefabricated sub-assemblies facilitates this (Gibb, 1999). The enhanced flexibility and adaptability allows owners to respond to varying market needs (e.g. temporary facilities, future relocation, reconfiguration, and renovation, etc.). From another perspective, prefabricated units may also facilitate the deconstruction process if they can be easily dismantled from the structure and transported offsite. Easily stackable units (cladding systems, curtain walls, steel beams, etc.) will further reduce transportation costs to off-haul materials (Fletcher et al. 2000). Potential assemblies may include wall systems, MEP assemblies, pre-cast panels, floor systems and structural systems. (Pulaski et al. 2003)
7. **Reduced overall life cycle cost:** This can be achieved through more reliable factory-level quality control first time during construction and more efficient maintenance over the service lives of the products/ materials/ systems.

Table 3: Positive Impact of Prefabrication Supporting Sustainable Objectives

Attributes of Prefabrication	Life Cycle Cost	Safety/Health	Non-Renewable Resource Use	Material Waste
Increased potential of supply-chain integration to support sustainable goals	+/0	+/0	+/0	+/0
Safer working conditions	0	+	0	0
Reduced environmental impact	0	+	+	+
Economic Impact in local communities	+/-	+/-	+/-	+/-
Easier recycling of materials and supplies in an off-site environment	+/0	+	+	+
Enhanced flexibility and adaptability	+	0	+	+
Reduced overall life cycle cost	+	0	0	0

Note: '+' means positive impact; '-'means negative impact and'0' means no obvious impact

APPLICATION AND TESTING: THE AMERICAN INDIAN HOUSING INITIATIVE

This research is currently a key focus of the American Indian Housing Initiative, a continuous effort by university partners to address the housing crisis facing American Indians. The mission is to adapt and deploy regionally appropriate sustainable building technologies on American Indian reservations. In the meantime, an educational exchange of cultural values and sustainable development strategies is achieved through collaborative and interdisciplinary partnerships. To date, nine projects have been built across the Northern Plains using strawbale and other sustainable building technologies (AIHI website). AIHI projects also serve as full scale project case studies and laboratories for research in the lean and green research initiative at Penn State. Designed and built under the leadership of faculty and students, the projects offer opportunities to test new lean and green concepts and research strategies.

A unique feature of AIHI projects with respect to prefabrication strategies is the high value placed on schedule (projects are built in "blitz-build" environments) and the desire to incorporate appropriate volunteer and semi-skilled labor in projects (reducing construction costs). The use of prefabrication strategies to achieve the compressed schedule must be carefully balanced between the desires to maximize volunteer labor. Thus an improved taxonomy of prefabrication techniques and their relationship to sustainability goals must be developed to guide decisions about the design and production planning on AIHI projects.

DESIGN FOR PREFABRICATION IN AIHI BUILDING SYSTEMS

The design-build environment of AIHI projects permits a rigorous exploration of the relationship between design choices, prefabrication strategies, and the resulting implication for on-site production and labor utilization. Three building systems of AIHI projects are currently the focus of this effort:

Site-built Strawbale Walls

All the elements that go into the wall are prefabricated onsite such as rebar staples, lath, pins, window bucks, and customized bales with specific dimensions. Raising bale walls is the biggest event onsite over the three weeks. Bales are stacked in a running bond; followed by horizontal and vertical strapping, pre-cut rebar driven at appropriate courses (typically every 3 or 4 courses) and staples at each corner. Pre-cut lath is then attached to both interior and exterior wall surfaces through certain stabilizer or strengthener (i.e. pins, Z channels and J channels). When lath is done, the wall is ready for stuccoing. The pre-assembly phase of the straw walls has been found to take more time and energy than the wall construction itself, however a primary contributor to the efficient construction of the wall.

Preassembled Roof Structure

Structural Insulated Panels (SIPs) are selected for roof systems. Their sound thermal and structural properties as well as the use of environmental friendly materials (e.g. OSB panels made of renewable wood products) suit the sustainable goals of this project. Another big advantage is that these panels can be easily erected by hand (unless they are in very large sizes then mechanical equipment will be needed). Working closely with the manufacturer in Montana (R-Control and Big Sky Insulation), the project team plans to have the preparatory work take place onsite while the bale walls are under construction. By doing so, work flows are streamlined with desired production rate; labor is well used onsite; quality & safety is secured; and cost benefits (material & labor) are achieved as well.

Onsite Prefabricated Glazing Frames

Polygal's Polycarbonate sheets are used on the clerestories of this project due to their insulating, light-transmitting and reflective qualities. The sheets are cut to desired sizes at an onsite workshop, fixed between onsite-prefabricated wood frames and then lifted and installed at their final positions on the roof frame. This system design combined with on-site prefabrication allows large surfaces of AIHI buildings to be glazed at a minimal cost, and meanwhile it enables the construction of durable and high quality frames by volunteers in a factory environment created on site.

Lessons

Lessons learned in this research to date are the result of continued efforts to refine the AIHI building model, and also to develop a long-term construction and economic development plan for the Northern Cheyenne Tribe.

- Design for physical and sequential independence between volunteer friendly construction and skilled work, for example straw walls and MEP work.
- Work with manufacturers to refine production of factory elements that can be pre-assembled on site with limited need for heavy equipment, for example maximizing the use of SIP roof panels, but limiting their size to panels that can be hand-set.
- Develop specially insulated glazing systems that can be fabricated locally to replace expensive windows, thus maximizing daylight without sacrificing energy efficiency.
- Develop reliable vendor relationships on supply chains for new and unfamiliar materials such as straw bales, fly ash (for stucco), and wheat board.
- Modularize and prefabricate building elements on site in preparation for blitz-build assembly of building components.
- Designs envelop systems to be high-mass and energy efficient systems (plastered strawbale) constructed on-site. These systems, although less likely to transport as prefabricated elements, maximize the use of volunteer labor.

CURRENT PROJECT AND FUTURE RESEARCH

In the summer of 2005, AIHI partners will construct an Early Childhood Learning Center (ECLC), a 4000 SF childcare facility for Chief Dull Knife College in Lame Deer Montana. The largest project so far in AIHI series, the ECLC will have the following features:

- **Funding**: This project is funded though grants from Housing for Urban Development, United States Department of Agriculture, and the National Science Foundation.
- **Design-build Project Team**: The team consists of faculty and students from architecture, architectural engineering and landscape architecture degree programs at the Pennsylvania State University and University of Washington.
- **Design Goal**: A LEED certified green building is being pursued. The design features durable and insulating strawbale construction, an SIP roof frame, radiant floor heating, evaporative cooling, CO2 monitoring, and digital climate control.
- **Schedule:** The superstructure for the ECLC will be completed in three weeks by the AIHI team, with the remaining work to be completed by tribal members.
- **Workers**: Mostly unskilled or semi-skilled volunteers except for sitework, foundations, and MEP work.

This project is currently being planned through students in three courses, the AIHI course, and graduate courses in production management and virtual design and construction. A detailed short interval production schedule and labor utilization plan is integrated with design details to maximize both prefabrication and the use of volunteer labor. The results of this research will be applied directly into the next phase of the AIHI program, in which a combined housing and economic develop program will be implemented. A key feature of this program will be the construction of modular utility cores by tribal members in a combined skill building and homeowner training environment. The cores will then be combined with shallow foundations, straw wall envelops, and SIP roof frames to take advantage of the appropriate prefabrication and labor utilization strategies found in this research.

DISCUSSION AND CONCLUSIONS

The evaluation of prefabricated systems in economic terms is highly influenced by local labor costs. Significant additional benefits exist however, to the use of prefabricated systems in green buildings. This research shows that proper design and use of assessment criteria containing both lean principles and green performance properties can help a design-build project team identify both the narrow and broad impacts of prefabricated systems in green construction at an early stage and thus establish the basis for most of the decision-makings occurring afterwards. Further research will be conducted upon this and a framework for decision support in selecting various prefabricated systems for GDB buildings will be developed.

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