
SUSTAINABLE VALUE ON CONSTRUCTION PROJECTS AND LEAN CONSTRUCTION

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ABSTRACT

Lean production is a systemic approach to meeting customer expectations, whatever they value, by reducing waste. At first glance, lean then could only contribute to sustainability, while sustainability is achieved only if the customer values sustainability. The paper has two objectives. One is to examine whether sustainability is feasible using lean production with sustainability as an added value. The second objective is to examine how current lean construction tools and methods impact the construction and operation of sustainable facilities. The authors also suggest how these lean construction tools and methods have evolved to contribute to green construction. For this study, the authors interviewed lean adopters and conducted literature surveys on lean principles and methods, and its impacts on the economic, social and environmental sustainability.

KEY WORDS

lean construction, sustainable construction, sustainable assessment, sustainability

INTRODUCTION

The construction industry is one of the largest and most important industries, yet at the same time is one of the largest polluters (Horvath, 2004). Therefore, the construction industry has the potential to make a positive impact on sustainable development. Lean construction can be one approach to this by introducing social and environmental issues as new values. The most widely accepted definition of sustainable development is from the Brundtland Commission, which was set up by the United Nations. In the commission's report, *Our Common Future* (1987), the Commission defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Sustainable development does not focus solely on environmental issues. More broadly, sustainable development policies and practices can be categorized into three areas: economic, environmental, and social. The term, "triple bottom line" evolved as a basis for sustainable development (Elkington, 1997). In practical terms, the triple bottom line expands the

income statement, the traditional company reporting framework, to take into account environmental and social performance in addition to financial performance. Elkington (1997) proposed these three values for use in strategic decision-making.

Some people may ask lean practitioners whether lean is green. Many researchers have reported that lean construction increases environmental benefits by eliminating waste, preventing pollution and maximizing the owners' value (Huovila and Koskela, 1998; Lapinski et al., 2006; Luo et al., 2005; Ferng and Price, 2005; Riley et al., 2005). Yet others have reported no appreciable relationship between lean and green in the manufacturing industry (Helper and Clifford, 1997). Several studies even argue that lean shows a negative impact on environmental performance (Cusumano, 1994; Rothenberg et al., 2001). Since one of the main purposes of the lean system is to maximize value for the customer rather than to reduce environmental impact, lean does not always assure a positive environmental effect. Therefore, the question mentioned before is not appropriate and should be modified.

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Can lean contribute to sustainability? Although the process of sustainable construction may not always ensure a sustainable result, lean can contribute to sustainability by prioritizing expenditures. This happens because one of the priorities of sustainable development or sustainable construction is reducing the demand of resources that impact the environment throughout the entire life cycle of a facility. Considering this, lean can contribute to sustainability by prioritizing expenditures. This works to reduce demand for energy, water, and materials during the construction, operation, and disposal of the facility, but only when the customer values sustainability. Lean is a systemic approach to meeting the customer's values, whatever they may be.

The purposes of this paper are to examine how the current lean construction methods impact the sustainability of capital projects and to suggest how these lean construction methods might evolve to contribute to green construction.

In this paper, the authors reviewed publications on lean and sustainability, and interviewed managers and front line supervisors who used lean tools. Some of them used lean for sustainability while most did not. The authors used the interviews to investigate the potential of lean methods for a future approach to sustainability. The study also identifies the relationships between lean construction methods and their impact on the economic, environmental, and social aspects of construction projects. It is noted that the outcomes, including their effectiveness, was not measured due to a lack of cases. Therefore, through the interviews and a literature review, the study is limited to investigating the potential of lean for sustainability.

THE CONCEPTUAL RELATIONSHIPS BETWEEN LEAN PRINCIPLES AND SUSTAINABLE CONSTRUCTION

While lean construction literature has mainly focused on dealing with problems and challenges that arise on the construction site, some research has investigated lean construction from the view of the whole life cycle of a project. It has been suggested that lean philosophies, which provide the conceptual basis, and lean construction methods and tools have great possibilities for sustainable construction (Huovila and Koskela, 1998). They (1998) argued

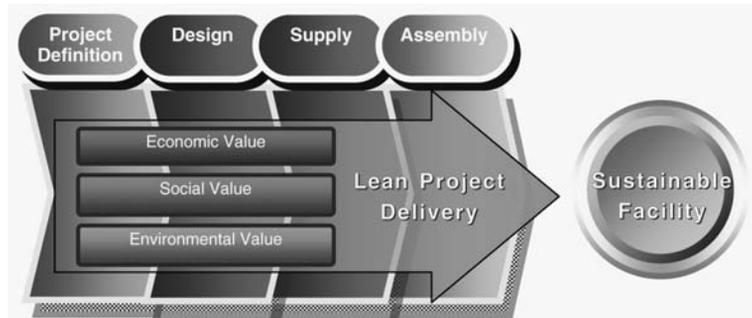
that the principles of lean construction contribute to the sustainability objectives by:

- Eliminating (material) Waste—minimizing resource depletion and pollution
- Adding Value to the Customer—minimizing resource depletion, pollution, while matching business and environmental excellence.

While some research has focused on the synergy between lean construction methods and sustainable construction in the economic, social and environmental aspects (Hawken et al., 1999), most studies have focused on lean construction methods as a means of reducing initial costs and eliminating waste rather than increasing the environmental performance of the project over the entire life cycle (Lapinski et al., 2006; Degani and Cardoso, 2002; Horman et al., 2004; Riley et al., 2005). Assessing the effectiveness of lean tools and methods in these studies is limited to the economic needs and values of the customers. Although current customers are becoming more aware of social and environmental values as well, their main concerns are how the environmental benefits may be achieved with no additional upfront costs. The relationship between sustainable development and lean production has been addressed by Horman (Horman et al., 2004). According to them, while the area of sustainability focuses on the design of the building, previous lean production mainly focused on the construction process. Considering that most lean construction practices deal with the problems on construction sites and lean construction considers controlling production a key activity, this idea seems reasonable at first glance. However, by limiting the role of lean within the construction phase, it fails to take into account the lean project definition and design phases in the early stages of a project. Lean practices could be implemented in the design phase of the construction project to reduce costs and enhance sustainability. For instance, Value Stream Mapping could be used all the way from the design through the construction phase.

Figure 1 illustrates the conceptual relationship between lean and sustainability. The four interconnecting phases of the Lean Project Delivery System (LPDS) extending from project definition to design, supply, and assembly are used to illustrate the lean

FIGURE 1. Conceptual relationship between Lean and Sustainability.



construction process (Ballard, 2000). In addressing sustainable issues, such as economic, social, and environmental values as the requirements of an owner, lean may act from the project definition to the construction phase for a sustainable facility.

THE RELATIONSHIPS BETWEEN LEAN METHODS AND SUSTAINABLE IMPACTS

The same four interconnecting phases of the LPDS are used to provide a framework for the implementation of lean construction methods in the construction industry. This section addresses how lean construction methods are applied to construction projects and how these methods can contribute to the sustainability of the projects.

Lean Project Definition

Value Definition. Defining value and waste is critical in lean production. Value management in lean production is an attempt to maximize value and eliminate waste. Recently more studies have introduced the environment as an additional “dimension of value” for sustainable facilities (Horman et al., 2004; Lapinski et al., 2005). In these studies the environmental values include: minimal building impact, maximum building system efficiency, efficient energy usage, reduced waste, and a healthy and productive environment for occupants. Although it is difficult to measure the social impact of facilities and the resulting measurements may be somewhat subjective, they have been critical issues in the practice of architecture industry. In the earlier stages of a given project, designers used to study the social impact of facilities on humans and communities. While architects and landscape designers have studied social, cultural, and ethical impacts such as changes in

human behavior, the health of occupants, and community relations, contractors have shown little concern for the social impacts of facilities. Even though contractors have difficulties in identifying, measuring, and reducing the social impact of facilities, they should try to identify, measure, and overcome these effects during the construction phase of a project. Lean practitioners may implement this process by communicating with the community, sociologists, and future occupants of a facility throughout the construction phases. Lean construction needs to define sustainable values including economic, environmental and social values as critical factors in implementing sustainable construction.

Contracts and Delivery Methods for Lean Construction. The contract type and delivery method of a construction project do not appear to directly impact the sustainable construction of facilities. However, selecting an appropriate contract type and delivery method for a construction project provides the basis for the sustainability of facilities indirectly by eliminating contractual barriers that prevent communication and innovation among designers and contractors. Contracting organizes the project delivery processes so that lean methods can be facilitated. Several innovative contract types and delivery methods are considered to provide a good environment for sustainable construction: Performance-based Contracting, and Integrated Project Delivery.

Higher technical performance, maintaining an environmentally-friendly construction site, and forming a close relationship with the community can be achieved by communication between project team members in the early phases of a project.

Horman et al. (2004) proposed that Performance-based Contracting (PBC) is a technique which defines all aspects of an acquisition around the purpose and required performance of facilities, not just the construction process. Green facilities usually require inventive techniques and materials that are difficult to adopt for inexperienced architects or engineers. Therefore, the information regarding these techniques and materials should be provided by specialty contractors and suppliers in the design phase of the construction project. This method helps the specialty contractors and suppliers suggest innovative ideas in the early phases of a construction project for the sustainable performances that the owner requires. These ideas may help a project team improve cost effectiveness, technical performance, and constructability of a facility while reducing unnecessary material, energy, and waste by trying to maximize the performance of a facility.

Integrated Project Delivery (IPD) is both the name of a relational contracting method and a company which implements the method. Westbrook and several other contractors formed an IPD team which is aimed at maximizing value and minimizing waste at the project level (Ballard et al., 2007). The IPD is a relational contracting method that employs two principles to govern the team relationship, maximizing the collaboration between stakeholders. First, all primary team members (PTMs) are responsible for the provisions of the prime contract with the client while the single contract binds the IPD team, as one entity, to the client. Second, all PTMs share the risk and profit for the project performance. With IPD's relational contracting method, the goal of "one for all and all for project" seems to be achievable.

The IPD may help stakeholders collectively improve in terms of both quality (i.e. performance of a facility and environmental and social impact of the project) and efficiency (i.e., production efficiency). When sustainable value is an important factor during in a construction project, the IPD is a contract form which helps a project team find sustainable indicators and improve the factors throughout the project.

Lean Design

Design is a process incorporating various construction techniques and materials to produce value to an

owner. This process is important considering the effects it has on the overall life of a facility. Design of a sustainable construction project is especially critical because green materials, resources and construction technologies require comprehensive coordination for the best application in green facilities. The impact of this phase on the operation and maintenance phase are remarkable. Romm (1994) stated that a mere one percent of the initial costs in the early phase of a project address 70 percent of its life cycle costs.

In order to minimize environmental impacts and energy consumption during the construction of sustainable facilities, several lean design methods could be implemented: Integrated Design (Whole system design), Target Costing, and Set-based Design.

Integrated Design is one of the most critical methods for sustainable construction (Hawken et al., 1999; Riley et al., 2004; Horman et al., 2004; Lapinski et al., 2005). A key feature of this method is to integrate various green materials and construction technologies by encouraging stakeholders in the design phase to maximize the sustainability of a facility while reducing the need for energy, equipment, or material. As other lean methods have evolved for sustainable construction, integrated design practices should be modified for environmental purposes (Horman et al., 2004). Horman et al. (2004) insisted that "integrating design and construction processes early in the project enabled multiple and significant synergies to be realized between sustainability and construction process efficiency." Moreover, early involvement of specialty contractors and suppliers in the design phase allows more possibilities for sustainability of a project (Riley et al., 2005). Environmental and social specialists may also enhance the relationship between the community and the health of its occupants by getting involved during a project.

Target costing is a strategy that states a building should be built within the budget specified (Ballard et al., 2007). Target costing in the construction industry is the practice of allocating the maximum amount of a construction budget for the construction subphases or functions of a facility. This method can reduce unexpected increases in cost during the construction phases by defining the scope and costs in the planning and designing phases. According to

an interview with Boldt Construction, the two most important aspects are getting everyone involved in the design process as soon as possible, and forming a multidisciplinary design team. This team includes the architect, the general contractor, the specialty contractors, the functional agents, and most importantly, the customer. Identifying the expectations of the customer is integral in beginning the process of target costing. The owner's defined value of the building can vary greatly from what the general contractor or architect might consider as the value. Letting the customer describe and contribute to the ultimate definition of the value on each project is an important concept for lean construction.

Target Costing is not examined for the purpose of sustainability. This lean method, however, may contribute to sustainable construction. This practice prevents the possibility of an unnecessary increase in facility performance or a waste of resources with pre-specified functions, capacities, and specifications.

When Boldt employed target costing for the St. Olaf College Fieldhouse project, they saved one percent of the total budget, while delivering the value that the customer had requested. Although environmental and social impact was not assessed, it can be expected that unnecessary resource depletion was avoided and the relationship among stakeholders improved throughout the project.

Set-based Design has the possibility of contributing to sustainable construction, although it has not been examined for sustainability. This approach explores all applicable "design criteria" or design options from the beginning of the design stage, rather than making a "design decision" to determine the design at the last responsible moment, which may not impact the overall project schedule. (Ballard et al., 2007) This strategy requires the designers to pursue several different design approaches in parallel with each other gradually eliminating alternatives. This is in contrast to the usual method in which a design approach is decided upon early on in the process. By avoiding the premature elimination of design alternatives, the set-based design method has a greater potential of producing an optimal design solution, thereby reducing the risk of enormous rework and wasted effort, which will cause unnecessary cost increases and conflict between stakeholders.

Lean Supply

Just-in-time (JIT) could also be either an environmentally-friendly method or not. JIT reduces the potential of damage to inventory and material consumption (Riley et al., 2005). This method may reduce the various sources of extra inventory. JIT can enhance manageability and vice versa. In the reliable work condition, JIT helps contractors save inventory-related costs by lessening the inventory level. At the same time, however, the frequent transportation of inventory and materials may cause an increase in volatile organic compounds (VOCs) and CO₂ emissions. Several lean plants have recognized that a JIT strategy has caused more air emissions of VOCs in the plants, while also contributing to the flexibility of operations and reducing inventory level (Rothenberg et al., 2001). Therefore, the plants have reconfigured some of their lean management principles to reduce their air pollution emissions. They started to increase painting batch sizes in order to reduce air emissions of VOCs, despite the fact that it conflicts with the JIT practices. Even though applications in the manufacturing industry and construction industry are not exactly the same, it is necessary to take note of the probabilities and possibilities of negative environmental impacts from lean adaptation. In spite of the environmental and social issues caused by frequent transit to construction sites, JIT may enhance the sustainability of the construction process. JIT was implemented in construction projects to prevent the damage of inventory and additional work.

GS Construction & Engineering (GS C&E), a general contractor in Korea, established two systems for JIT: Rebar Processing Plants and GS- Bar Bending Automation System (GS-BAS).

GS C&E established two rebar processing plants in 2005, and has supplied rebar to construction sites where GS operates. The goals of the rebar processing plants are to minimize the rebar loss rate, meet the exact specification of reinforcing processes, eliminate the space for inventory loading and field working, and manage the material effectively.

Construction field offices, an estimating firm (which is a subsidiary of the GS C&E), and rebar processing plants cooperate with one another through the rebar processing plant operating system,

which is called GS-BAS. This system automates shop drawing preparation, material quantity calculation, procurement, and on-site project management.

With the orders from job sites, the rebar processing plants can produce 280 thousand tons of rebar yearly. Rebar losses can now be kept below 1 percent, saving the company about \$40 million a year. Moreover, JIT reduced rebar inventory and unnecessary movement of rebar on the job sites. However, despite these improvements in cost effectiveness, inventory maintenance, and material consumption during the construction phase, JIT in the construction industry results in frequent deliveries, which generate more emissions. Therefore, one must consider the construction project from a holistic perspective when proposing JIT as a method for increasing the sustainability of a project.

Lean Assembly

Prefabrication may be an approach for sustainable construction. Horman et al. suggested economic, social, and environmental indicators affecting sustainability and showed a qualitative assessment of these indicators (Horman et al., 2005 in Luo et al., 2005). They examined the quality of work, the component and material supply chain, the flexibility of the work process, delivery and shipping, transportation energy, local labor, working condition, etc. The features of prefabrication on sustainable construction include:

- Increased potential of improved supply chain integration of green materials
- Safer working conditions
- Reduced environmental impact due to transferring workers, machines, stacked materials, temporary structures and onsite activities to a prefabrication plant
- Reduced material depletion due to easier recycling of materials in an off-site environment
- Better manageability due to enhanced flexibility and adaptability
- Reduced overall life cycle cost
- Reduced economic impact in local communities

Prefabrication may have both sustainable benefits and disadvantages depending on the exact conditions of a project. These impacts fall into three categories: economic, social, and environmental. Thus, economically, one advantage is the reduced cost of

prefabricated units as opposed to on-site units. Socially, the working conditions are safer and more stable in prefabricated construction than they are on-site. Environmentally, large scale prefabrication may improve the supply chain for green materials by ensuring a reliable supply chain of environmentally friendly materials, which is one of the goals of sustainable construction (Luo et al., 2005).

Yet, there are some problems as well. Economically and socially, less local labor is needed, thus the salaries of the workers do not contribute to the local economy. Environmentally, this process may consume more energy for transportation of prefabricated assemblies to the site with the attendant increase in air emissions.

A contractor trying to implement sustainable construction should first define and evaluate sustainable issues before beginning a construction project. Only after investigating the issues, can the contractor identify both the benefits and disadvantages of prefabrication. Those factors can be referred to later in selecting the best procurement method using a holistic view over the life cycle of a project.

Executed Over the Whole Delivery Process

Visual Management. There are several lean visual methods which could help promote sustainable construction. They include the 5S and Value Stream Mapping (VSM), or streamlining of the process.

The 5S, which stand for separate, straighten, scrub, systematize, and sustain/standardize, are used to create and maintain a clean, orderly and standardized work place. This method is often considered the first step companies take in their lean journeys, since it serves as the foundation of future continual improvement efforts. The aims of the 5S mentioned above improve profitability, manageability, efficiency and safety a job site.

Moreover, this method creates a sustainable construction site by cleaning the workplace and reducing air pollution, which may also improve the relationship with the community. The U.S. Green Building Council (USGBC) established criteria for green design. The criteria are largely outlined in the USGBC's Leadership in Energy and Environmental Design (LEED) Rating System. The USGBC requires the design of a sediment and erosion plan

for sustainable sites, in which the 5S may contribute. The 5S may help a contractor increase productivity while protecting laborers from injuries and occupational health hazards by providing clean and accident-free work areas. Evaluation of projects based on LEED metrics allows people to award various levels of certification, which brings “standardization, validity, and visibility to projects and the green design process” (USGBC, 2007).

Many studies suggest that VSM is one of the best visual tools that show the flow of both information and material. Therefore it is very useful for process owners to understand the generation and flow of value and waste during project processes for the sustainability of the facilities (Riley et al., 2005; Lapinski et al., 2005, 2006). Traditionally, VSM has been used to assess process time and inventory levels to define value and waste, because these factors are key constituents for economic purposes. The objective in using VSM is to improve the process of production by working to eliminate economic waste. By identifying value, waste, and flow of material and information, VSM can make construction processes more transparent and predictable. This feature of VSM may lessen the risk of investment and improve management by helping process owners have a thorough understanding of the processes. This lean method, however, may be used not only for economic purposes, but also social and environmental purposes by adding sustainability-related data into the map. In addition to time and inventory, the waste of resources, creation of pollution, resource consumption, safety, and interaction with the community may be mapped. In 2006, the U.S. Environmental Protection Agency (US EPA) incorporated the traditional VSM with environmental considerations. This new method developed a “materials line” on the bottom of a value stream map that shows two types of data:

- The amount of raw materials used by each process
- The amount of materials that end up in the product and add value from a customer’s perspective.

The materials line is similar to the “time line” on traditional value stream maps, and can be developed for any type of resource (e.g. water, energy, total materials, and/or a critical substance used in the prod-

uct), environmental pollution (e.g. emissions, waste, wastewater, and hazardous wastes) or social impacts (e.g. noise, relationship with the community).

In order to identify an owner’s capital development process over the whole project, an extended VSM covering the programming to operational phase was developed (Lapinski et al., 2005). This map was used to recognize the environmental value and waste of a sustainable construction project.

According to interviews with project managers at Walbridge Aldinger, the logistical plan helps stakeholders eliminate waste and improve the flow of work on a job site. The logistical plan is a map that illustrates the organization and equipment on a construction site, the movement of these entities, the storage and flow of material, and generation and cleaning of physical waste. The logistical plan also supports a project manager to organize current and planned activity on the site. Walbridge implemented the Logistical Plan to improve the manageability of cost effectiveness and to reduce resource depletion. These benefits are gained by providing effective communication and coordination between stakeholders, improving material management, and minimizing work conflicts. The site logistics planning is an efficient way to let any stakeholder who looks at a plan understand where they should and should not be. The logistical plan can be updated by the stakeholders anytime a site logistics plan changes.

Kaizen and Kaikaku. Kaizen, which means continuous improvement in Japanese, is one of the core concepts of lean production, not only for economic purposes, but also for social and environmental purposes in sustainable construction. Kaizen is one of the primary ways of implementing other lean methods, ranging from the 5S to much more complex lean construction tools. After an analysis of the current state, Kaizen is a useful tool for continuous improvement by using a delivery process mapping method (Lapinski et al., 2005). Kaizen provided the basis for a total process approach to sustainable project development. This concept was used at the South Campus Office Building project in Torrance, CA (Horman et al., 2004). Kaizen plays a key role in improving the current status for sustainable construction. All sustainable indicators may be improved through Kaizen.

Another potential tool for pursuing sustainable “perfection” is Kaikaku (Kaizen events), which means a rapid process of improvement. It is a team activity designed to eliminate waste and make rapid changes for product and process improvement in the workplace. This strategy is employed to unite workers from multiple organizational levels in addressing problems and improving processes. When implementing the chosen improvements, the team rapidly employs inexpensive solutions usually within three days. It is possible for the improvements to be rapidly implemented by changing the process. Kaikaku can reduce pollution, energy, and material waste/depletion. However, this tool may cause environmental or social problems in the event it pursues only economic targets without the presence of a qualified Environmental Health and Safety (EHS) staff. Sometimes the economic benefits and environmental/social benefits conflict with each other. For this reason, the EHS staff must participate in Kaizen events due to the possibility of non-compliance and exposure of workers to health hazards. Suggestions may be made by EHS staff to facilitate the process (US EPA, 2006).

ASSESSING LEAN CONSTRUCTION METHODS ON SUSTAINABILITY

Assessment

The field of sustainable building is as hard to define as the concept of sustainability is to measure. Indicators are needed to define criteria, and to measure industry performance. These indicators could be technical solutions with varying properties, e.g. emissions levels of CO₂, SO₂ or NO_x can be used directly to quantify environmental impacts (Huovila, 1999).

The challenge to measuring sustainability is that sustainability is not very quantifiable (Kwong, 2004). Therefore, it is very difficult to quantify both direct and indirect impacts of sustainable features, including initial cost savings, energy savings, O&M savings, productivity improvement, improved relationship with the community, water consumption, pollution, safety, and prestige. Moreover, it is more difficult to identify the comprehensive link between lean implementation and sustainability.

However, despite of the difficulties of quantifying, measuring, and evaluating sustainability, there have been endeavours to establish sustainability measurement systems. In the US, LEED is used;

in the UK, the Building Research Establishment’s Environmental Assessment Method (BREEAM) is used. Environmental impacts, such as ecology, land usage, energy, materials, waste, employee well-being and health, management, pollution, transport, and water, are examined by the use of BREEAM.

These rating systems are very useful for promoting green buildings. However, these systems limit their concerns to the environment rather than expanding their areas of concern to sustainability. Therefore, in this paper the authors present a sustainable performance indicator based on the LEED checklist and the list of benefits of sustainable buildings (Yates, 2001). Some indicators are not limited to just one category. For instance, “Pollution and Waste Management” may contribute to each environmental, economic, and social purpose. Environmental and social impact include externalities, in which the cost of environmental and public infrastructure impacts. These externalities are not normally charged directly to a construction project. These benefits and indicators of sustainable buildings include:

1. Economic perspective
 - Financial Profitability—remaining competitive in the market place is affected by upfront and operating costs, productivity, sales, market profile, and level of competitiveness
 - Investment Risk Avoidance—increasing predictability, profitability, and flexibility help to reduce risk.
 - Management and Auditability—The benefits of good management are intangible but are nevertheless important to sustainability because of the amount of control they give.
 - Technical Performance—durability, service life, maintainability, R-value, strength and constructability.
2. Environmental perspective
 - Sustainable Site—the design of a sediment and erosion plan must occur.
 - Resource Depletion—Locally, and globally the exploitation of resources cause significant environmental and social disruptions, therefore limiting consumption is key.
 - Pollution and Waste Management—Considerable environmental and health problems locally and globally occur due to pollution; construction waste is mostly landfilled at present.

- Energy Consumption—critical to sustainable construction and facilities.
3. Social perspective
- Health and Safety—The indoor environmental health and occupational safety of a facility is a major concern. Addressing these issues increases loyalty, productivity of tenants, and makes an organization more attractive to employees.
 - Prestige—Having a sustainable facility creates an appealing place of business for all concerned.
 - Relationships with the Community—Curing the problems of various types of pollution (e.g., noise, air, and water) create a better public image and raise status.
 - Relationships among stakeholders—Maintaining stakeholder relationships over the long term and demonstrating mutual respect is essential for the success of sustainable construction projects

In the construction industry there are few performance measurement tools that link lean efforts and green results directly, because it is hard to measure all sustainable impacts of lean implementation. For instance, in order to measure the performance of the integrated design, all measurable benefits should be counted (Hawken et al., 1999). Traditional construction performance measurement systems with fragmented views may miss the benefits from integrated design. In the holistic perspective, integrating expensive sustainable resources and technologies could reduce overall upfront construction costs.

EVALUATION SUMMARY

The purpose of assessing the construction methods described in this part is not to compare these practices, but rather to evaluate the current application of lean construction methods based on sustainable development and construction philosophies, and to explore better approaches to applying lean construction.

Table 1 illustrates an assessment of the previously discussed methods on the sustainability of a construction project. Each lean method shows concrete relationships between the current lean construction methods and the sustainable performance of a facility, while several practices reveal positive relationships as well as negative relationships. Most lean

construction methods provide positive economic impacts for sustainable facilities while showing several negative impacts on the social and environmental aspects. Environmental and social impacts do not tend to be directly felt by the stakeholders in a particular project (Yates, 2001). They are harder to trace to a specific operating method than to allocate to an operating method. Stakeholders, therefore, ignore the social and environmental impacts and remove them from the decisions of a commercial facility construction project. In order to assess the application of these methods, qualitative information such as how the tools will be used should also be considered.

CONCLUSION

Lean philosophy provides a concrete basis not only for economic, but also social and environmental purposes in sustainable construction by improving the delivery processes of green facilities. This paper demonstrated that high levels of building sustainability can be achieved with smart and effective project execution resulting in fewer additional upfront costs from the qualitative perspective.

The key impacts of using lean construction methods for the purpose of sustainability are categorized as follows:

- Economic perspective: possible upfront cost reduction, resource savings, operating cost reduction, and high performance capability
- Social perspective: workplace safety, occupant health, community well-being, loyalty among stakeholders, and external image improvement
- Environmental perspective: reduced resource depletion, pollution prevention by eliminating waste, and resource preservation.

Several lean construction methods were examined in this paper. Although many other lean construction practices were not examined for sustainability, these practices may have the possibility for sustainable purposes but need their impacts to be quantified. The difficulty in understanding and quantifying the impacts of lean construction methods is perhaps one reason that stakeholders hesitate to introduce these methods to achieve sustainable facilities. This is one reason most publications assess lean construction methods only from the economic perspective. Further research will be conducted

TABLE 1. Lean methods and sustainable impacts.

Lean Project Delivery Phases	Lean Methods	Economic Impacts	Environmental Impacts	Social Impacts
Lean Project Definition	PBC	<ul style="list-style-type: none"> • Innovative idea in the early phases • Improved cost effectiveness • Increased constructability 	<ul style="list-style-type: none"> • Innovative idea in the early phases • Reduced material and energy depletion 	<ul style="list-style-type: none"> • Innovative idea in the early phases
	IPD	<ul style="list-style-type: none"> • Efficient production 	<ul style="list-style-type: none"> • Improved environmental performance 	<ul style="list-style-type: none"> • Improved social performance
Lean Design	Integrated Design	<ul style="list-style-type: none"> • Maximized economic performance (cost, efficiency, etc.) through early involvement of stakeholders • Expected synergy between stakeholders 	<ul style="list-style-type: none"> • Easy to integrate various green materials and construction technology • Reduced energy, equipment, or material consumption 	<ul style="list-style-type: none"> • Enhanced relationship with community • Enhanced health of the occupants of a facility
	Target Costing	<ul style="list-style-type: none"> • Avoided design “busts” of a facility by defining the scope and construction costs in the early phases of a project 	<ul style="list-style-type: none"> • Prevented possibility of unnecessary material consumption and waste 	<ul style="list-style-type: none"> • Improved relationship among stakeholders
	Set-based Design	<ul style="list-style-type: none"> • Reduced risk of rework and/or subpar facility performance 	<ul style="list-style-type: none"> • Reduced risk of rework and/or subpar facility performance 	<ul style="list-style-type: none"> • Prevented risk of conflict between stakeholders
Lean Supply	JIT	<ul style="list-style-type: none"> • Reduced inventory-related cost • Reduced inventory damage • Increased manageability • Reduced additional work 	<ul style="list-style-type: none"> • Reduced material depletion • Sustainable job site 	<ul style="list-style-type: none"> • Increased emissions caused by frequent delivery
Lean Assembly	Prefabrication	<ul style="list-style-type: none"> • Better manageability due to enhanced flexibility and adaptability • Reduced overall life cycle cost 	<ul style="list-style-type: none"> • Improved supply chain integrated of green material • Reduced environmental impact due to temporary workers, machines, structures, and onsite activities • Easier recycling of materials 	<ul style="list-style-type: none"> • Safer work condition • Reduced economic impact in local community

(continued on next page)

TABLE 1. (continued)

Lean Project Delivery Phases	Lean Methods	Economic Impacts	Environmental Impacts	Social Impacts
General	5S	<ul style="list-style-type: none"> Improved productivity 	<ul style="list-style-type: none"> Reduced air pollution 	<ul style="list-style-type: none"> Safer work condition Enhanced relationship with community
	VSM	<ul style="list-style-type: none"> Improve production process by elimination economic waste Improved manageability Reduced the risk of investment 	<ul style="list-style-type: none"> Easy to find out waste, creation of pollution 	<ul style="list-style-type: none"> Easy to find out the process relating hazard material and noise
	Logistical Plan	<ul style="list-style-type: none"> Improved manageability of inventory and labor 	<ul style="list-style-type: none"> Reduced transportation on job site 	<ul style="list-style-type: none"> Easy to find out the process relating hazard material and noise
	Kaizen	<ul style="list-style-type: none"> Basis for economically continuous improvement 	<ul style="list-style-type: none"> Basis for environmentally continuous improvement 	<ul style="list-style-type: none"> Basis for socially continuous improvement
	Kaikaku	<ul style="list-style-type: none"> Basis for economically rapid improvement 	<ul style="list-style-type: none"> Basis for environmentally rapid improvement May cause problems without the presence of EHS staff members 	<ul style="list-style-type: none"> Basis for socially rapid improvement May cause problems without the presence of EHS staff members

regarding the assessment of not only the economic, but also social and environmental impacts of lean construction methods. The research will also work to develop a framework that supports the selection of various lean construction practices for sustainable facilities.

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APPENDIX—INTERVIEW QUESTIONS

For this paper, the authors interviewed with several lean adopters, which are Integrated Project Delivery (IPD™), Boldt, Walbridge Aldinger, and GS Construction. The following is interview questions between the authors and the interviewees.

1. Please describe the project(s) on which lean principles and tools have been implemented. (type, size, location, contract structure, incentives, etc.)
2. Please tell the project's 'lean' story (general question; where did the idea come from, sequence of implementation)
3. What lean principles or tools were implemented?
4. Why were lean principles or tools implemented?
5. How were lean principles or tools implemented? (Sequence of events, external or internal consultants, early wins, etc.)
6. What are the impacts of lean implementation on sustainability?
7. What are the potentials of lean construction tools for sustainability?
8. How do you structure lean project organizationally and contractually?

