# CONTRIBUTIONS OF LEAN CONSTRUCTION TECHNIQUES TOWARDS SUSTAINABLE CONSTRUCTION TECHNIQUES BY REDUCING SOCIAL, ECONOMIC, AND ENVIRONMENTAL COSTS OF CONSTRUCTION PROJECTS

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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## INTRODUCTION

*To what extent can a framework be established by which lean construction techniques are used to promote more sustainable construction in terms of lessening environmental, economic, and social impacts?*

Achieving sustainable development in the built environment is a complicated yet necessary task. The construction industry is responsible for a large proportion of the negative effects we see on the environment and our societies. As it exists currently, the construction and use of the built environment account for 40% of greenhouse gas emissions annually (Crawford, 2022). These emissions are split into two subsets: building energy use (27%) and embodied emissions (13%) (Architecture2030, 2023), the latter of which are the emissions that are generated from construction materials and processes. In addition to greenhouse gas emissions, the construction industry is also one of the largest producers of waste: in the United States alone, 600 million tons of construction and demolition debris were generated in 2018 (U.S. Environmental Protection Agency, 2022). These wastes and emissions from the built environment are only expected to continually increase as demands on the construction industry grow from larger numbers of people demanding a better quality of life.

Recent efforts have been made to improve the sustainability of the built environment through new technologies and environmental regulations, yet energy consumption and greenhouse gas emissions have continued to rise (Crawford, 2022). The construction industry therefore presents a vital opportunity for decreasing global energy consumption and emissions. Between the two subsets of global greenhouse gas emissions coming from the built environment, there has been a more intense focus on reducing building energy use emissions compared to the focus on reducing embodied emissions. While this is necessary given that building energy use emissions are twice as large as embodied emissions, attention needs to be given to aspects of embodied emissions such as construction methods and materials to ensure that all facets of the construction industry have a sustainable future. Such improvements to the construction industry and built environment can be achieved through the utilization of sustainable construction (SC) techniques.

SC techniques aim to reduce the environmental, social, and cultural impacts caused by traditional construction methods, and therefore meet the goals of sustainable development (Huovila & Koskela, 1998). Sustainable development, as defined by the Brundtland Report, is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). There are three objectives of sustainability to be considered within sustainable development: environmental, societal, and economic growth. One of the most well recognized symbols of sustainable development is the LEED rating system, which "provides a framework for healthy, efficient, carbon and cost-saving green buildings" (U.S. Green Building Council, 2023). However, these sorts of frameworks are not useful for all types of infrastructure within the built environment, meaning that more general sustainability frameworks and methods of construction must be established. The construction industry has made this effort in achieving sustainable development by incorporating more environmentally friendly, socially aware, energy efficient, and waste conscious methods of construction (Marhani, Jaapar, Bari, & Zawai, 2013). Among the most prevalent of these novel construction methods is the utilization of lean construction (LC) techniques.

LC techniques were originally derived from the manufacturing industry. They aim to minimize site waste, construction time, and overall construction costs through better project management (Marhani, Jaapar, Bari, & Zawai, 2013). While the priorities of LC techniques are not typically associated with sustainable development, LC parallels sustainability by reducing the number of resources used and promoting efficiency in construction projects. The priorities of SC are centered more on reducing negative social and environmental impacts. These two paradigms do share general ideas of promoting resource efficiency and minimizing waste, meaning that LC could have additional benefits in terms of environmental and social sustainability (Francis & Thomas, 2020). However, if LC becomes purely focused on the economic benefits in the form of reducing cost and increasing profits, it might lead to negative environmental and societal impacts (Song & Liang, 2011). For this reason, LC needs to be evaluated not just from an economic aspect, but through the lens of sustainability to ensure that construction practices have benefits for current and future generations. In this paper, the similarities of the motives and methods for both LC techniques and SC techniques will be examined by way of a literature review. From this analysis, a framework will be developed to determine how infrastructure projects can be made more sustainable in terms of lessening environmental and societal impacts through the implementation of LC techniques.

## BACKGROUND

### *Lean Construction*

The infrastructure sector has fallen behind in industry development, as labor efficiency in the construction industry has decreased while efficiency in all other industries (except farming) has at least doubled since the 1960s. Additionally, 70% of construction projects are either over budget or delivered late (Lean Construction Institute, 2022). LC practices, modeled after the lean production theory developed in the early 20$^{th}$ century by a Toyota engineer, are one way in which industrial efficiency can be largely increased. One of the first projects to use LC in design and construction (although “lean construction” had yet to exist) was the Empire State Building, which went from design to completion in under three years, ahead of schedule and under budget

(Lean Construction Institute, 2022). The modern concept of "lean construction" was coined in 1993 by the International Group for Lean Construction (Banna, 2017). The Lean Construction Institute defines LC as such:

> Lean construction is a project delivery process that uses Lean methods of maximizing stakeholder value while reducing waste by emphasizing collaboration between teams on a project. The goal of Lean construction is to increase productivity, profits, and innovation in the industry (Lean Construction Institute, 2022).

Lean philosophy is applied in many fields, but it is especially attractive for use in the construction industry because it "contrasts the conventional practices of the industry by introducing the concept of 'value'; and provides a broader meaning to the term 'waste' in construction" (Francis & Thomas, 2020). LC techniques are meant to solve some of the inefficiencies in the construction industry by identifying these wastes and values and working to minimize and maximize them, respectively. Values in construction are associated with productivity and therefore with human labor. Calvert et al. (1995) define labor productivity as "the determination of the time required for an average operative to carry out a particular task in accordance with a specified method and standard of performance." Other examples of values in construction are maximizing building system efficiency, producing a healthy and productive environment for occupants, prioritizing community relations, and reducing costs for the client (Bae and Kim, 2007). Wastes in construction are defined as "non-value adding costs" by Buzby et al. (2002) or "any activity, which absorbs resources but creates no values" by Womack and Jones (1997). Typically, these wastes account for 30-35% of a construction project's production cost (Forsberg & Saukkoriipi, 2007). By the definition of waste given by Womack and Jones, adding value to a construction project is equivalent to removing waste. The seven wastes of lean thinking that should be eliminated from the construction process in order to add value are as follows: (Koskela, 2000, p. 57)

- lack of resources or their readiness, originating delays;
- Unnecessary stages and tasks;
- Unnecessary movement of materials,
- Equipment and people; excess of resources for the accomplishment of a task;
- Material inventories and respective declarations of material conformance;
- Excessive production due to the use of too many resources;
- Production deficiencies, originating correction and consequently the use of more materials and manpower.

When looking at the wastes given by Koskela above, they can be divided into two main groups (Forsberg & Saukkoriipi, 2007): use of resources and systems and structures. Use of resources includes waste associated with the inefficient use of materials, machinery, and skilled labor. Systems and structures includes waste associated with the structure of the construction industry such as inefficient planning processes, communication between clients and contractors, and approval times for land, machinery, materials, or procedures (Josephson & Saukkoriipi, 2005).

The most notable way LC can reduce waste in the construction industry through both the use of resources and systems and structures is by integrating all parties involved in a project. Most conventional construction projects use either design-bid-build or design-build contracts, which separate stakeholders of a project into smaller projects with their own separate contracts. With LC practices, there is only one contract between the owner, design team, and contractors, allowing every party to be contractually involved in each step of the design and construction process (Lean Construction Institute, 2022). This makes for more effective project delivery since the interests, objectives, and practices of all project stakeholders are aligned. Other techniques used in LC emphasize streamlining construction processes, conserving materials and resources, and utilizing automation where available, and will be explored later in this paper.

Overall, if LC techniques are successfully implemented by adding value and reducing waste in construction projects, the following outcomes can be achieved on infrastructure projects as summarized by Wodalski et al (2011). First, construction activities are structured more effectively, removing obstacles to completing work on time. Next, workflow is made more predictable, reducing waste and improving productivity. Finally, construction management is focused on the performance of the project as a whole rather than focusing on the completion of a particular activity. These outcomes correlate to large benefits in construction projects such as higher client and worker satisfaction, faster delivery of projects, and larger economic and environmental benefits.

*Sustainable Construction*

SC is the construction industry's contribution to sustainable development. SC is vital considering that "what we build today will provide the built environment of the future and will influence the ability of future generations to meet their needs" (Dickie and Howard, 2000). SC has been less well defined when compared to other construction frameworks given its relative newness. One strategy for SC was published in 2000 by the Department of the Environment, Transport, and the Regions of the United Kingdom, and details the ways that the construction industry could aid in achieving the goals for sustainable development (Pitt et al, 2008). These are as follows:

- Being more profitable and more competitive;
- Delivering buildings and structures that provide greater satisfaction, well-being and value to customers and users;
- Respecting and treating its stakeholders more fairly;
- Enhancing and better protecting the natural environment; and
- Minimizing its impact on the consumption of energy and natural resources.

These goals of SC as defined by the United Kingdom are relatively unique compared to SC goals of other countries. This is mainly because the United Kingdom considers infrastructure other than buildings, as well as the competitiveness of the construction industry, as being significant to future work in SC. When looking at other sustainable development plans, such as the Federal Sustainability Plan in the United States, SC is concerned almost exclusively with sustainability in buildings and not the entirety of the built environment (U.S. Environmental Protection Agency, 2023). Additionally, sustainability holds more weight in the building's use phase with respect to energy usage than it does in the materials or construction phases where sustainable materials or construction frameworks could be utilized. This being said, the United States has been globally impactful with their development of LEED, a framework for sustainable buildings.

The U.S. Green Building Council (USGBC) created LEED in 1998 and it is now the world's most widely used green building system. LEED's vision is that, through their framework, they can "transform how buildings and communities are designed, built and operated, enabling an environmentally and socially responsible, healthy, and prosperous environment that improves the quality of life" (U.S. Green Building Council, 2023). Green building codes such as LEED encourage a built environment that is focused largely on sustainability by saving money, lowering emissions, and creating healthy community spaces. To achieve LEED certification via the LEED scorecard, a building must meet prerequisites and can earn additional credits that "address carbon, energy, water, waste, transportation, materials, health, and indoor environmental quality" (U.S. Green Building Council, 2023). There are four levels of LEED certification, listed from lowest to highest number of credits: Certified, Silver, Gold, and Platinum. Across the globe, there are more than 120,000 LEED certified buildings today.

## LITERATURE REVIEW

There are several existing studies on the benefits of both LC and SC techniques when applied in unison in terms of environmental, economic, and social sustainability. The benefits that LC techniques alone bring to construction projects in terms of environmental and economic sustainability have also been studied. Economic and environmental sustainability of infrastructure projects are measured via parameters such as pollution, waste, natural resource consumption, and emissions (Francis & Thomas, 2020). Social sustainability in construction is described by Herd-Smith and Fewings (2008) as "the engagement among employees, local communities, clients, and the supply chain to ensure meeting the needs of current and future populations and communities." Valdes-Vasquez and Klotz (2013) believe that measures of social sustainability of a construction project also involve stakeholder satisfaction, training of disadvantaged people, and impact on a community. However, social sustainability is significantly more difficult to measure than environmental and economic sustainability as it is based off subjective opinion rather than objective statistics. Most past work compiled on the intersection of LC and SC is focused on the pillars of environmental and economic sustainability. Newer analyses of the benefits of either LC or SC attempt to quantify social sustainability via surveys of contractors, design firms, and communities which construction projects have impacted.

This paper will be based off an existing literature review by David Carvajal-Arango et al. found in the Journal of Cleaner Production, *Relationships between lean and sustainable construction: Positive impacts of lean practices over sustainability during construction phase* (Carvajal-Arango et al., 2019). Carvajal-Arango et al. effectively establish the relationships between the philosophies of LC and SC based on 117 articles written on LC, SC, or both. From the literature, the positive effects of LC on sustainability were defined and within these effects, the most mentioned practices were highlighted. Among these commonly mentioned positive outcomes of using LC techniques are "productivity increase, waste reduction, construction cost decrease, and construction time decrease." In general, it was found that LC and SC shared the most objectives in respect to improving the management of construction projects. It was also found that LC may not have directly positive impacts on each of these subsets of sustainability – rather, there is a positive but indirect relationship between the economic benefits from LC and the perceived environmental and social benefits (Carvajal-Arango et al., 2019).

## METHODS

The objective of this study was to establish a framework by which LC techniques can be used concurrently with SC techniques to promote environmental, economic, and social benefits in construction projects. When completing this framework, it was necessary to consider the wants and needs of all parties involved in a construction project to generate the most logical and effective use of LC techniques towards sustainable outcomes. The parties considered were those such as the contractor, the client, the community, the economy, and the environment with respect to how they respond to and what they value the most within the two construction ideologies: LC and SC. The literature review completed by Carvajal-Arango et al. established the practices and goals that LC and SC techniques share, but it did not offer suggestions for how LC techniques can be best utilized to have an intentionally sustainable outcome. Additionally, the Carvajal-Arango literature review was lacking some of the most recent studies completed in the fields of LC and SC which had a concentrated focus on impacts on social sustainability. Once reviewing the work compiled by Carvajal-Arango et al. with the purpose of understanding the similarities in LC and SC techniques, a systematic literature review of articles pertaining to LC and SC techniques was completed using resources from the Carvajal-Arango et al. literature review as well as resources found independently from the existing literature review. The literature review was conducted using electronic databases such as Science Direct, Google Scholar, and Web of Science as well as cross referencing citation lists between articles, especially those articles used in the Carvajal-Arango literature review. Articles that were selected for use in the literature review were full-text articles focused on either LC techniques, SC techniques, or the relationship between the two techniques.

The objectives of the literature review completed in this sociotechnical thesis were as follows: to substantiate the theoretical and practical similarities and differences between LC techniques and SC as outlined in Carvajal-Arango et al. (2019); and to subsequently determine the ways in which sustainable action could best be emphasized through utilizing the methodology of LC. When selecting which publications would be used in the literature review, it was important to consider papers which, when taken as a whole, could support the use of LC towards each of the three facets of sustainability. Once the LC techniques that correlate best with SC motivations were determined, a framework for how these practices might be applied to infrastructure in all phases of its lifespan was created based off the LEED v4.1 scorecard for building design and construction: new construction certification. The scorecard for building design and construction: new construction was selected as opposed to the scorecards for other aspects of the built environment such as existing buildings, neighborhood development, or cities and communities because LEED is most often utilized in new building construction (U.S. Green Building Council, 2019).

**RESULTS**

Thirteen publications were selected in addition to the literature review by Carvajal-Arango et al. to build the framework for how LC techniques can be best used to produce intentionally sustainable results in construction projects in all three facets of sustainability: environmental, economic, and social. Out of these thirteen publications, nine were used in the Carvajal-Arango et al. literature review and four were sourced independently of the review. The publications existed in three forms: literature reviews, case studies, and surveys. Literature reviews and case studies were most effective in analyzing the positive relationship between LC and SC ideologies both theoretically and in construction projects. These were useful for marking and detailing how specific LC techniques could be used to obtain sustainable outcomes, particularly with environmental and economic sustainability. Surveys were most useful in the literature review for assessing the impact of LC on social sustainability through determining attitudes of contractors and clients towards LC techniques. These publications are described below in Table 1, featuring the publication title and date, the publication author(s), a short description of the publication type and contents, and which areas of sustainable development (environmental, economic, and/or social) are related to LC techniques within the publication.

**Table 1. Publications Selected for Literature Review in Building a Framework for Incorporating Sustainable Construction in Lean Construction Techniques**

| Publication Title and Date | Publication Author(s) | Article Type and Description | Sustainable Construction Impacts |
|---|---|---|---|
| Contribution of the Principles of Lean Construction to Meet the Challenges of Sustainable Development (1998) | Pekka Huovila & Lauri Koskela | Case study; the first paper to draw on a relationship between LC and sustainable construction, discusses potential and profitability of LC techniques to promote sustainable discussion | • Environmental<br>• Economic |
| Lean and Green: Integrating Sustainability and Lean Construction (2004) | Michael Horman et al. | Case study; argues that LC techniques and sustainable construction have a common agenda for minimizing resources | • Environmental<br>• Economic |
| Sustainable Value on Construction Project and Application of Lean Construction Methods (2007) | Jin-Woo Bae and Yong-Woo Kim | Literature review; reviews publications that study LC techniques and the impacts of the environmental, economic, and social sustainability. | • Environmental<br>• Economic<br>• Social |
| Measurement of Waste and Productivity in Relation to Lean Thinking (2007) | Azam Forsberg & Lasse Saukkoriipi | Literature review; highlights how LC can be used to identify and reduce wastes in construction projects which coincides with the ideals of sustainable construction in terms of reducing the overall footprint of construction projects | • Environmental<br>• Economic |
| Green-Lean Conceptual Integration in the Project Design, Planning, and Construction (2009) | Patricia Martinez, Vicente Gonzalez, Eduardo Da Fonseca | Case study; conceptualizes an integration of the philosophies of sustainable construction and lean construction | • Environmental<br>• Economic |
| Understanding Construction Industry Experience and Attitudes toward Integrated Project Delivery (2010) | David Kent & Burcin Becerik-Gerber | Survey; looks at the attitudes of the construction industry towards integrated project delivery (IPD), an integral component of LC | • Social |
| Lean Construction Implementation and its Implication on Sustainability: A Contractor's Case Study (2011) | Lingguang Song & Daan Liang | Case study; describes the implementation of LC and its impact on environmental sustainability from the perspective of a contractor | • Environmental |
| Sustainability in Civil Construction Applied in the Construction Site Phase (2011) | E. Vasquez et al. | Case study; analyzes sustainability as applied to the construction site, presents possible environmental impacts to construction sites as well as solutions to alleviate these effects. | • Environmental<br>• Social |
| Lean and Green Construction: Lessons Learned from Design and Construction of a Modular LEED Gold Building (2012) | Kristen Parrish | Case study; presents how LC techniques were used in the construction of a LEED gold building in California in order to achieve sustainable development goals | • Environmental<br>• Social |
| Reducing Environmental, Economic, and Social Impacts of Work-Zones by Implementing Lean Construction Techniques (2014) | Ossama Salem et al. | Literature review; details the ways in which LC techniques can be used to minimize impacts on the environment, society, and economy in respect to pavement construction, maintenance, and rehabilitation | • Environmental<br>• Economic<br>• Social |
| Lean and Green: A Case Study to Examine Environmental Benefits of Lean Construction (2014) | Somik Ghosh et al. | Case study; examines how a healthcare facility that used LC techniques in the pre-construction and construction phases experienced environmental benefits compared to traditional construction techniques | • Environmental |
| Relationships between Lean and Sustainable Construction: Positive Impacts of Lean Practices over Sustainability During Construction Phase (2019) | David Carvajal-Arango et al. | Literature review; summarizes existing publications on the positive relationship between lean and sustainable construction with respect to the construction phase | • Environmental<br>• Economic<br>• Social |
| Lean Construction: Experience of US Contractors (2019) | Somik Ghosh & Jason Burghart | Survey; results from a survey conducted among the top 200 contractors of the United States as listed by *Engineering News-Record* on their opinions and familiarity with LC techniques | • Social |
| Assessing Psychological Safety in Lean Construction Projects in the United States (2021) | Sevilay Demirkesen, Emel Sadikoglu, Eshan Jayamanne | Survey; focuses on the impact of LC techniques on the psychological safety of employees as compared to the psychological safety of employees working on traditional construction projects | • Social |

## DISCUSSION

### *Lean Construction*

Construction projects that use LC techniques have consistently proven that they are effective in reducing construction times and costs; increasing productivity; improving project quality; decreasing consumption of materials, water, and energy; reducing emissions; and improving work conditions among many other benefits (Carvajal-Arango et al., 2019). Table 2 lists ten of the most effective LC techniques applied in the construction industry to increase value in construction projects. These ten techniques were selected intentionally to align with the motivations of SC with the intention of building a framework from the complementary parts of the two construction ideologies. Each of these ten LC techniques were also identified by the Carvajal-Arango et al. literature review.

**Table 2. Lean Construction Techniques Selected for Comparison with Sustainable Construction Ideologies**

| | Lean Construction Techniques | References |
|---|---|---|
| 1 | Value Stream Mapping (VSM) | (Bae and Kim, 2007) |
| 2 | Graphic Schedules | (Song and Liang, 2011) |
| 3 | Improvement Culture | (Bae and Kim, 2007) |
| 4 | Method of the 5S | (Salem et al., 2014), (Bae and Kim, 2007). |
| 5 | Prefabricated or Modular Construction | (Parrish, 2012), (Bae and Kim, 2007) |
| 6 | Collection, Classification, and Recycling of Construction Wastes | (Huovila and Koskela, 1998), (Vasquez et al., 2011) |
| 7 | Use of Regional Materials and Suppliers | (Vasquez et al., 2011) |
| 8 | IPD (Integrated Project Delivery) | (Ghosh et al., 2014), (Kent and Bercerik-Gerber, 2010) |
| 9 | Last Planner System | (Song and Liang, 2011), (Salem et al., 2014) |
| 10 | Pull Strategy | (Ghosh et al., 2014) |

It is necessary to define each of these LC techniques to form conclusions about the methods by which the above techniques might be used to promote sustainable outcomes on construction projects. Brief definitions of these ten LC techniques are given below:

- *Value Stream Mapping (VSM)* (Bae and Kim, 2007)
  VSM is a visual tool for stakeholders to understand the generation and flow of value and waste during project processes for sustainable facilities. VSM assesses process time and inventory levels to define value and waste. When used with LC techniques, VSM tracks economic, environmental, and social data such as waste of resources, creation of pollution, resource consumption, safety, and interaction with the community.

- *Graphic Schedules* (Song and Liang, 2011):
  Graphic schedules overlay daily activity scheduling information onto construction site plans. When activities and their locations are displayed with their relation to site plans, interference among activities, site logistics, and other project information can be analyzed. This prevents wastes generated by conventional construction schedules such as constraints, interruptions, waiting, and moving.

- *Improvement Culture* (Bae and Kim, 2007):
  Improvement culture is a core component of lean ideology in seeing economic, environmental, and social benefits. There are two facets to improvement culture: continuous improvement and rapid improvement. Through both forms of improvement, the goal is to incorporate more LC techniques to eliminate waste through improving design and production processes.

- *Method of the 5S* (Salem et al., 2014), (Bae and Kim, 2007):
  The 5Ss are *separate, straighten, scrub, systematize,* and *sustain/standardize.* The 5Ss are used to create and maintain a clean, orderly, and standardized workplace, and are often the fundamental step a company makes in incorporating lean ideologies.

- *Prefabricated or Modular Construction* (Parrish, 2012), (Bae and Kim, 2007):
  Prefabricated or modular construction has potential environmental, economic, and social benefits for those working on a construction site. Environmentally, prefabricated units see benefits from transferring workers, machines, materials, and onsite activities to a prefabrication plant where emissions can be better controlled. Economically, prefabricated units are much less expensive than fabricating those same units on site. Socially, when prefabricated units are built in a plant, these conditions are typically safer than those on a working construction site.

- *Collection, Classification, and Recycling of Construction Wastes* (Huovila and Koskela, 1998), (Vasquez et al., 2011):
  The collection, classification, and recycling of construction wastes is most notably an environmental benefit as it seeks to reduce the impact of construction projects by reducing life cycle costs. More valuable construction wastes such as wood or steel can be sold for economic benefit.

- *Use of Regional Materials and Suppliers* (Vasquez et al., 2011):
  Using regional materials and suppliers in construction projects is associated with social and environmental benefits. Local suppliers see economic benefits from the construction project's investment in the community. Environmental benefits are generated given that regional materials do not produce as many emissions in transport to construction sites.

- *Integrated Project Delivery (IPD)* (Ghosh et al., 2014), (Kent and Bercerik-Gerber, 2010):
  IPD is a delivery method for construction projects which involves single multi-party and shared risks and rewards contract. IPD aligns all project stakeholders with the project objectives, establishing a sense of teamwork. An integrated team leads to better results in all phases of a project and reduces overall project time and cost.

- *Last Planner System* (Song and Liang, 2011), (Salem et al., 2014):
  The last planner system is a project planning methodology that integrates three types of scheduling: master scheduling (overall execution plan for a construction project), look-ahead scheduling (detailed work to be done within a look-ahead time window), and weekly work planning.

- *Pull Strategy* (Ghosh et al., 2014):
  Pull planning requires "working from a target completion date backwards where tasks are defined and sequenced so that their completion releases work," (Ghosh et al., 2014). This allows for stakeholders to communicate what they need from other stakeholders to complete their tasks, therefore increasing efficiency and delivering more predictable project results.

The above LC techniques are effective in reducing the environmental, economic, and social costs in construction projects by reducing wastes that exist in typical construction projects. Many of these LC techniques revolve around reducing waste and adding value to the planning process in construction projects, which is where many inefficiencies and economic loss originates. VSM, graphic schedules, the method of the 5S, improvement culture, IPD, last planner system, and pull strategy are all examples of techniques that aim to streamline pre-construction and construction processes. These sorts of techniques most effectively add value to construction projects by introducing collaborative decision making and mutual respect and trust between stakeholders (Ghosh et al., 2014), aligning objectives and schedules of stakeholders, and reducing miscommunications that result in construction delays. The next primary way in which

LC techniques reduce waste and add value is with respect to the materials used in construction projects. From the techniques given in Table 2, prefabricated or modular construction, use of regional materials and suppliers, and collection, classification, and recycling of construction wastes all feature the ideology of removing wastes from and adding value to construction materials. Values added to construction materials based on these LC techniques include recycling materials for profit, using cheaper and more efficient materials, using materials that produce less transport emissions, or using materials whose utilization results in a direct investment of the surrounding communities. The final aspect of adding value to construction projects via the LC techniques listed above is the improvement of health and safety conditions for construction workers and community members. Ingrained in every one of the ten LC techniques is an increased focus on how pre-construction and construction processes as well as construction materials can be improved to better serve all stakeholders in a construction project.

### *Sustainable Construction*

Sustainability is divided into three facets: environmental, economic, and social sustainability. A more complete list of potential areas for sustainable impact within the construction industry after (Pitt et al, 2008) and (Carvajal-Arango et al, 2019) is shown below in Table 3.

**Table 3. Aspects of Sustainability in Construction Projects**

| Environmental Impact | Economic Impact | Social Impact |
|---|---|---|
| Waste Creation and Management | Construction Costs | Safety and Health |
| Energy Use | Quality | Working Conditions |
| Water Use | Construction Time | Respect for the local community |
| Reuse and Recycling | Value Creation | Influence on the local economy |
| Atmospheric Emissions | Uncertainties and Risks | Community Disturbance |
| Noise Emissions | | Relationships and Communication Improvement |
| Material Consumption | | Enhance Employee Skills |
| Affection to Soil Quality | | Diversity in Teamwork and Equal Employment Opportunities |
| Affection to Fauna and Flora | | Employee Retention |
| Embodied Energy | | Project Declaration of General Interest |
| Visual Impact | | Public Participation and Control on the Project |

From the sustainability impacts given in Table 3, it becomes apparent that SC is focused largely on the potential environmental and social impacts that construction projects could produce. Additionally, the impacts listed are mainly applied to the pre-construction and construction phases of a building which is atypical of the conventional definition of sustainability in construction. In the past, SC has been associated with the use phase of a building. However, to build a framework that utilizes LC techniques to achieve sustainable outcomes, these sustainable outcomes must be brought into the pre-construction and construction phases for useful comparison with LC.

*Lean and Sustainable Construction Framework*

To build a framework that considers both LC and SC as having the same end goals, we must consider the differing means and motivations by which they reach the goal. Both LC and SC have a conceptual focus of reducing resources used and waste produced for a construction project, albeit in different phases of the project's lifespan. This focus is achieved by an emphasis on adding values to building processes for SC and adding values to building design and construction via construction materials and processes for LC. The contrasting thought processes behind the two construction methods in terms of where value should be added in a building's lifespan leads to a common output of high-performance processes that generate high performance buildings (Horman et al., 2004). This conceptual connection between LC and SC is laid out in Figure 3, after Figure 1 in Horman et al (2004).

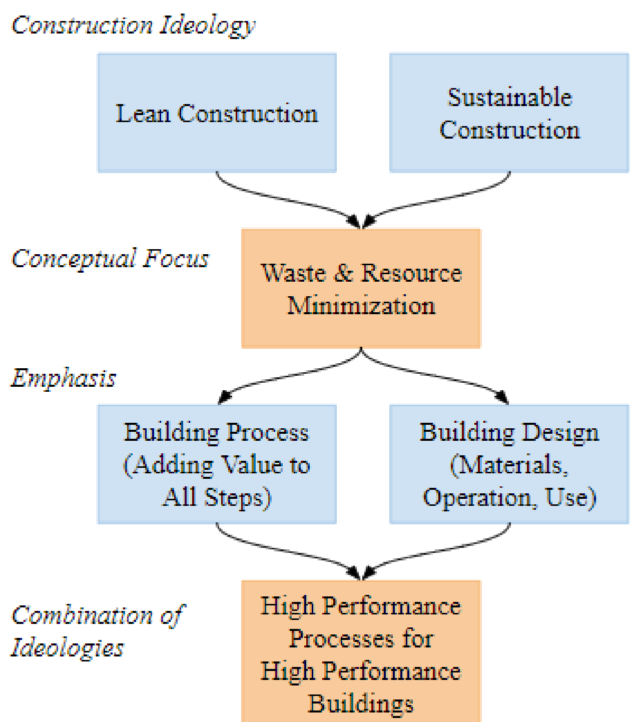


**Figure 1.** Conceptual Connection between Lean Construction and Sustainable Construction

The conceptual connection between LC and SC is useful for determining how the two construction ideologies might be combined so that the benefits are received from each. When comparing the LC techniques and the aspects of SC detailed in Tables 2 and 3, there are a few common characteristics: waste reduction, worker health and safety, increased efficiency and productivity, improved environmental and resource management, reduced costs, and overall added value and quality to the construction process (Carvajal-Arango et al., 2019). These common objectives are listed in Table 4 in their entirety along with the publications, LC techniques as given in Table 2, and sustainable impacts as given in Table 3 that support them, after Table 4 in Carvajal-Arango et al. (2019).

Table 4. Relationships Between Lean Construction and Sustainable Construction

| Lean & Sustainable Construction Techniques | Applicable Lean Techniques (Table 2) | Applicable Sustainable Impacts (Table 3) | References |
|---|---|---|---|
| Reduction of Waste | All LC Techniques | Waste Creation and Management, Reuse and Recycling, Energy Use, Water Use, Construction Time | (Horman et al., 2004), (Bae and Kim, 2007), (Huovila and Koskela, 1998), (Ghosh et al., 2014), (Martinez et al., 2009), (Vasquez et al., 2011), (Song and Liang, 2011), (Forsberg and Saukkoriipi, 2007), (Salem et al., 2014) |
| Improvement of Environmental Management | VSM, Graphic Schedules, Improvement Culture, Prefabricated Construction, Recycling Construction Wastes, Use of Regional Materials and Suppliers, | All Environmental Impacts | (Huovila and Koskela, 1998), (Ghosh et al., 2014), (Bae and Kim, 2007), (Martinez et al., 2009), (Vasquez et al., 2011), (Song and Liang, 2011), (Salem et al., 2014) |
| Value Maximization | All LC Techniques | Value Creation | (Horman et al., 2004), (Huovila and Koskela, 1998), (Bae and Kim, 2007), (Forsberg and Saukkoriipi, 2007) |
| Improvement of Health and Safety Conditions | Improvement Culture, Method of the 5S, Prefabricated Construction | Safety and Health, Working Conditions, Relationships and Communication Improvement, Diversity in Teamwork and Equal Employment Opportunities, Employee Retention, Enhance Employee Skill | (Bae and Kim, 2007), (Kent and Bercerik-Gerber, 2010), (Vasquez et al., 2011), (Song and Liang, 2011), (Salem et al., 2014), (Ghosh and Burghart, 2019), (Demirkesen, Sadikoglu, and Jayamanne, 2021) |
| Increased Process Efficiency and Productivity | All LC Techniques | Construction Time, Waste Creation and Management, Community Disturbance, Public Participation and Control on the Project, Energy Use, Material Consumption, Reuse and Recycling | (Forsberg and Saukkoriipi, 2007), (Bae and Kim, 2007), (Martinez et al., 2009), (Parrish, 2012), (Ghosh and Burghart, 2019) |
| Increased Product Quality | Improvement Culture, Prefabricated Construction, Use of Regional Materials and Suppliers | Quality, Value Creation, Safety and Health, Respect for the Local Community | (Parrish, 2012) |
| Improvement of Resources Management | VSM, Graphic Schedules, Improvement Culture, Method of the 5S, Prefabricated Construction, Recycling of Construction Wastes, Use of Regional Materials and Suppliers, IPD | Waste Creation and Management, Material Consumption, Embodied Energy, Construction Costs, Construction Time | (Horman et al., 2004), (Bae and Kim, 2007), (Martinez et al., 2009), (Forsberg and Saukkoriipi, 2007), (Song and Liang, 2011), (Ghosh et al., 2014), (Ghosh and Burghart, 2019), (Vasquez et al., 2011) |
| Costs Reduction | All LC Techniques | Construction Costs, Construction Time, Reuse and Recycling, Value Creation, Public Participation and Control of the Project | (Bae and Kim, 2007), (Martinez et al., 2009), (Forsberg and Saukkoriipi, 2007), (Vasquez et al., 2011), (Salem et al., 2014) |
| Employee Satisfaction | Graphic Schedules, Improvement Culture, Method of the 5S, Prefabricated Construction, Use of Regional Materials and Suppliers, IPD, Last Planner System, Pull Strategy | Safety and Health, Working Conditions, Relationships and Communication Improvement, Enhance Employee Skills, Diversity in Teamwork and Equal Employment Opportunities, Employee Retention | (Kent and Becerik-Gerber, 2010), (Parrish, 2012), (Ghosh and Burghart, 2019), (Demirkesen, Sadikoglu, and Jayamanne, 2021) |

The discussion above has established two facts so far: 1) relationships between LC and SC as given in Table 4 show that LC is effective in providing sustainability benefits in the environmental, economic, and social aspects of a construction project through adding value; and 2) when combining the ideologies of LC and SC, sustainability benefits can exist within all phases of a building's lifespan instead of solely in the building's use phase. The next concern in building a construction framework that utilizes LC in achieving SC goals is to determine which LC techniques do the best in producing sustainable results for all stakeholders in a project. When considering the stakeholders in a traditional view of a construction project, there is only the client (the owner and the public) and the contractor. These two parties share social and economic concerns, but there is a lack of focus on the environment. When combining the ideologies of LC and SC, the environment must become a stakeholder to effectively incorporate the three aspects of sustainability. The concerns and priorities of each of these parties are as follows (Huovila and Koskela, 1998):

- from the *owner* and *public's* point of view:
  *Conformity to business processes; Location; Delays; Adding Value to Life; Life Cycle Costs; Final Product Conditions,* because they influence both the success of the project investment from the owner and the usefulness of the project to the public.

- from the contractor's point of view:
  *Worker Safety; Comfort; Embodied emissions; Cost of materials and operations; Environmental regulations; Distance to project site; Skilled/Unskilled labor available,* because they could greatly influence construction costs.

- from the environment's point of view:
  *Environmental burdens during construction and operation phases; Service life length, Risk for deterioration; Convertibility and flexibility; End-of-life operations,* because they pose the largest environmental burdens during a project's intended service life.

These theoretical priorities for a construction project based on LC and SC, along with the common relationships presented in Table 4, were used to develop an example of a requirements framework for a structure (building) that satisfies both LC and SC demands. The framework's formatting was based on the most current version of the LEED building design and construction: new construction certification scorecard for sustainable structures (U.S. Green Building Council, 2019). There were several prerequisites of a structure to meet the demands of using both LC and SC techniques on a project. Based on the above discussion in terms of which LC techniques could provide the greatest sustainability benefits for the most stakeholders, the following prerequisites were decided upon in addition to the existing prerequisites for LEED certification: integrated project delivery; diverse hiring of contractors and suppliers; collection, classification, and recycling of construction wastes; costs reduction (construction, administrative, and maintenance); substantial service life; management of structure against deterioration; and building life cycle impact reduction. Other prerequisites, such as all the prerequisites for the "energy, atmosphere, and indoor environment," were taken directly from the LEED scorecard. Potential lower priority, but still beneficial practices for a building aiming to utilize LC and SC techniques were given as credits. Examples of these credits are method of the 5S, graphic schedules, use of regional suppliers, and use of regional materials. The development phase for each of these practices was also specified as existing in the pre-construction, construction, use phase, or end-of-life phase of a building. These were specified in the framework as phase 1, 2, 3, and 4, respectively. This was different from the LEED scorecard which focuses on sustainability in the use phase of a building. The framework for LC and SC is given below in Table 5.

**Table 5. Framework for Lean and Sustainable Construction**

| 0 | 0 | 0 | | BUSINESS & CONSTRUCTION PROCESSES | PHASE | 3 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | Integrated Project Delivery | 1, 2 | Required |
| Y | | | Prereq | Diverse Hiring of Contractors and Suppliers | 1, 2 | Required |
| | | | Credit | Method of the 5S | 1, 2, 3, 4 | 1 |
| | | | Credit | Graphic Schedules | 1, 2 | 1 |
| | | | Credit | Use of Regional Suppliers | 1, 2, 3 | 1 |

| 0 | 0 | 0 | | LOCATION | PHASE | 3 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | High Priority Site and Equitable Development | 1, 2, 3 | Required |
| | | | Credit | Sensitive Land Protection | 1, 2, 3, 4 | 1 |
| | | | Credit | Surrounding Density and Diverse Uses | 3, 4 | 1 |
| | | | Credit | Traffic & Delay Communications | 2 | 1 |

| 0 | 0 | 0 | | SUSTAINABLE SITES | PHASE | 3 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | Collection, Classification, and Recycling of Construction Wastes | 2, 4 | Required |
| Y | | | Prereq | Construction Site Pollution Prevention | 2, 4 | Required |
| | | | Credit | Site Assessment | 1 | 1 |
| | | | Credit | Protect or Restore Habitat | 2, 3, 4 | 1 |
| | | | Credit | Open Space | 1, 2, 3 | 1 |

| 0 | 0 | 0 | | COSTS REDUCTION | PHASE | 0 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | Construction Costs Reduction | 1, 2, 4 | Required |
| Y | | | Prereq | Administrative Costs Reduction | 1, 2, 3, 4 | Required |
| Y | | | Prereq | Maintenance Costs Reduction | 3 | Required |

| 0 | 0 | 0 | | ENERGY, ATMOSPHERE, and INDOOR ENVIRONMENT | PHASE | 5 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | Fundamental Commissioning and Verification | 1, 2 | Required |
| Y | | | Prereq | Minimum Energy Performance | 3 | Required |
| Y | | | Prereq | Building-Level Energy Metering | 2, 3 | Required |
| Y | | | Prereq | Fundamental Refrigerant Management | 3 | Required |
| Y | | | Prereq | Minimum Indoor Air Quality Performance | 3 | Required |
| | | | Credit | Optimize Energy Performance | 3 | 1 |
| | | | Credit | Minimum Indoor Air Quality Performance | 3 | 1 |
| | | | Credit | Sound Insulation and Noise Reduction | 3 | 1 |
| | | | Credit | Thermal Comfort | 3 | 1 |
| | | | Credit | Low-Emitting Materials | 2, 3 | 1 |

| 0 | 0 | 0 | | SERVICE LIFE AND END OF LIFE USE | PHASE | 1 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | Substantial Service Life | 1, 3 | Required |
| Y | | | Prereq | Management of Structure Against Deterioration | 3 | Required |
| | | | Credit | Structure can be Converted to Serve Other Purposes | 4 | 1 |

| 0 | 0 | 0 | | MATERIALS and RESOURCES | PHASE | 2 |
|---|---|---|---|---|---|---|
| Y | | | Prereq | Storage and Collection of Recyclables | 2, 3 | Required |
| Y | | | Prereq | Building Life-Cycle Impact Reduction | 1, 2, 3, 4 | Required |
| | | | Credit | Use of Regional Materials | 2, 3 | 1 |
| | | | Credit | Construction and Demolition Waste Management | 2, 3 | 1 |

## CONCLUSIONS

The ideologies of SC and LC are relatively new and not yet widely accepted by the construction industry, but when used concurrently have the potential to reduce embodied emissions and increase sustainability in the built environment. A literature review of multiple publications on the relationship between LC and SC proved that there are shared ways to reduce the environmental, economic, and social impacts of construction projects through implementation of the ideologies. LC and SC share motivations of waste reduction, increased productivity, and a larger focus on worker health and safety through streamlined construction processes. By building a theoretical framework of how LC and SC ideologies can be combined effectively, it is hoped that these sorts of methodologies will be better understood and put into practice more frequently to increase the efficiency of a historically inefficient field. The integration of LC and SC offers a tool for working towards construction projects that leave positive footprints on contractors, clients, society, and the environment in the name of sustainable development for future generations.

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