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Sustainability in Construction: Using Lean Management Principles to Reduce Waste

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SUSTAINABILITY IN CONSTRUCTION: USING LEAN MANAGEMENT PRINCIPLES TO REDUCE WASTE

by

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ABSTRACT

SUSTAINABILITY IN CONSTRUCTION: USING LEAN MANAGEMENT PRINCIPLES TO REDUCE WASTE

by

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Under the Supervision of Professor Jin Li

The construction industry is facing many challenges. There are growing consumer demands for sustainable building. The construction industry generates a significant portion of the waste going into landfills. The construction industry has failed to keep pace with productivity in the manufacturing industry. Through adoption of Lean management principles, the construction industry can become more sustainable while increasing productivity. The literature was evaluated for three concepts: Lean management principles interaction with sustainability, the current state of sustainability in the construction industry, and the current state of Lean management principles in the construction industry. Lean management philosophies interactions with sustainability has been heavily studied in the manufacturing industry, but rarely so in the construction industry. The construction industry has been slow to adopt Lean philosophies, as construction presents unique challenges not present in manufacturing. There are emerging technologies in construction that enhance sustainability and Lean philosophies. Through analysis of the few case studies performed on Lean construction, an early model of Lean impacts has been proposed.

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LIST OF ABBREVIATIONS

BIM	Building Information Modeling
C&D	Construction and Demolition
CIP	Continual Improvement Process
CPSA	Construction Phase Sustainability Actions
CSA	Critical Sustainability Aspects
DOR	Digital Obeya Room
EPI	Environmental Performance Index
eVSM	Environmental Value Stream Mapping
IoT	Internet of Things
ISM	Interpretive Structural Modeling
KPI	Key Performance Indicators
LC	Lean Construction
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LM	Lean Management
LP	Lean Practices
LPI	Logistics Performance Index
PDCA	Plan Do Check Act
SEM	Structural Equation Model
SME	Small-Medium Enterprises
SPP	Sustainable Project Planning
Sus-VSM	Sustainable Value Stream Mapping
TBL	Triple Bottom Line
VSM	Value Stream Mapping
WFM	Waste Flow Mapping

I
INTRODUCTION

Consumers are increasingly demanding more sustainable initiatives from companies. Share price of Fortune 500 Firms consistently rises after announcing environmental initiatives (Wassmer, C. Cueto, and N. Switzer 2014). In 2018 32% of construction firms responded that most of their projects were green. That number is predicted to be 45% in 2021, a 41% growth in 3 years. The main driving force behind these changes are client demands, as opposed to environmental regulations (Dodge Data & Analytics 2018). The market is trending towards sustainability and conscientiousness.

The traditional reductionist viewpoint is that environmentally focused and goals and economically focused goals present a trade-off; one must be sacrificed for the other. The more sophisticated approach is that the trade-off can be minimized by exploiting leverage points where waste and inefficiency have negative impacts on both environmental and economic fronts (Zaidi, Ahmed, and Uddin 2019). The construction industry is positioned to take advantage of these leverage points for both economic and environmental gains. The construction industry has suffered from stagnant productivity relative to the manufacturing sector and generates a significant portion of the waste going into landfills.

According to McKinsey Global Institute Analysis, construction productivity has remained mainly the same since 1995 while manufacturing productivity has almost doubled (McKinsey Global Institute 2017). Part of this disparity can be explained by the manufacturing sector increasingly adopting Lean philosophies, and the construction industry has been slow to adopt these philosophies.

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Construction and Demolition accounts for a large portion of waste in landfills. C&D debris accounts for more than twice what is generated from municipal solid waste, also known as residential waste (US EPA, OSWER, ORCR 2018). Most of the sustainable construction has been focused on the function of the building, not on the construction process and the waste stream. Through inclusion of Lean philosophies, the construction industry can increase productivity and reduce the waste generated.

Lean production is a management philosophy which evolved from Toyota's Production System in the 1930s. The term "Lean" was initially used in 1988 and included distilled down to five principles (Womack and Jones 1997):

1. Value: Precisely specify value by specific product
2. Value Stream: Identify value stream for each product
3. Flow: Make value flow without interruptions
4. Pull: Introduce steps where a continuous flow is possible
5. Perfection: Pursue perfection

Womack and Jones define Lean as "a way to do more and more with less and less – less human effort, less equipment, less time and less space – while coming closer and closer to providing customers exactly what they want". They also go on to define the seven types of waste:

1. Transportation
2. Inventory
3. Motion
4. Waiting
5. Overproduction
6. Over-processing
7. Defects

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The goal would be to use foundational principles of Lean to make continuous and incremental improvements to the product and the process by adding value and eliminating waste.

There are many Lean tools available, each with guidelines for implementation. There are philosophical commonalities between many of the popular tools, such as 5S (Fig 1.1), Plan Do Check Act (PDCA) (Fig 1.2), Continuous Improvement Cycle (Fig 1.3), and Kaizen (Fig 1.4). Each of these tools are cyclical in nature; iteratively receiving feedback to continually improve. These tools also necessitate two-way flow of information: communicating the goals and directives from management and communicating the impacts of change and input from functional personnel. This information flow engages functional personnel in making changes that align with management goals and makes feedback readily available for management. The mechanics of the tools are less important than the Lean philosophies they are built upon, the information flow, and cyclical nature to continuously improve. 5S, PDCA, CIP and Kaizen are depicted in figures to show their underlying philosophies of iterative and cyclical processes seeking continual improvement.

Fig 1.1 5S

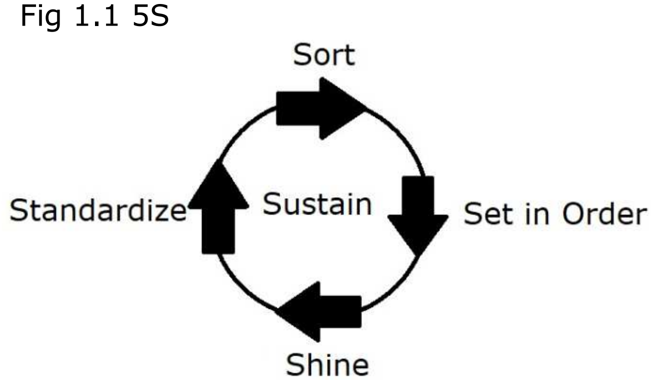

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Fig 1.2 PDCA

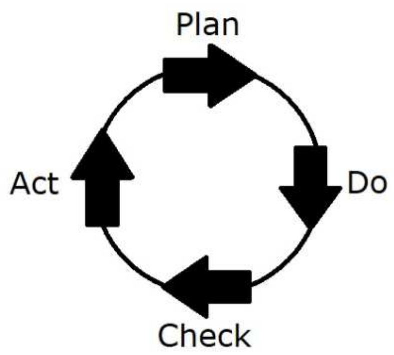


Fig 1.3 CIP

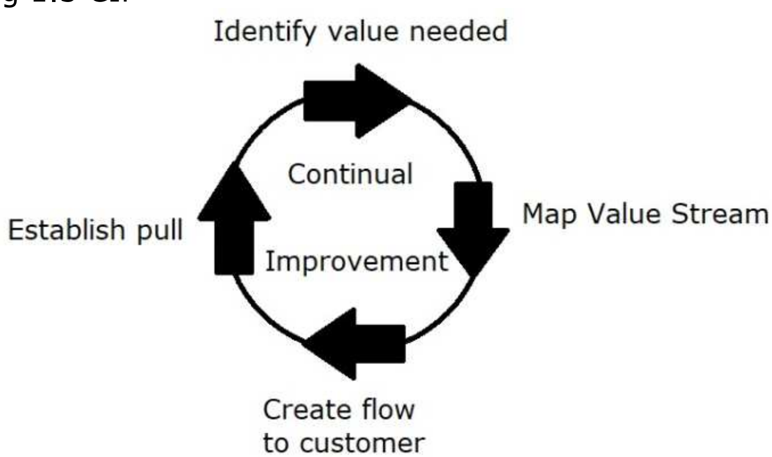
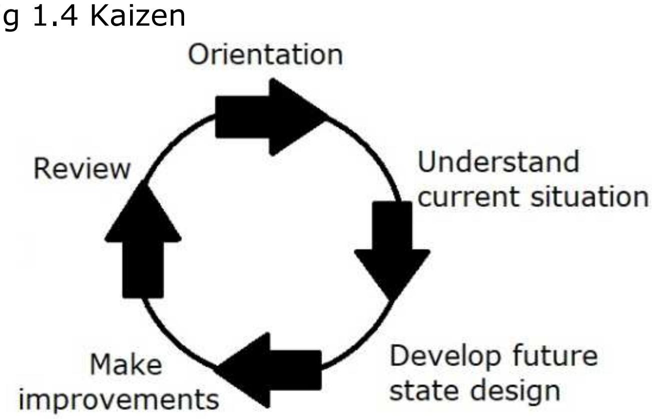


Fig 1.4 Kaizen



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Definition of Sustainability: "Meeting the needs of the present without compromising the ability of future generations to meet their own needs." According to United Nations Brundtland Commission, 1987 (ramsthaler@un.org 2014), The UN further defines three pillars that comprise sustainability: social, economic, and environmental. This is also known as the Triple Bottom Line (TBL).

- Economic – Practices that support long-term economic growth (University of Mary Washington 2015)
- Social – Managing impacts on people, maintaining quality relationships with stakeholders and the community (Karbassi 2019)
- Environmental – Protect and sustain the health of the ecosystem, including air, water, wildlife, and natural resource integrity (EPA n.d.).

More sophisticated models for sustainability have been proposed, such as the Circles of Sustainability model, which uses the 4 pillars of Economics, Ecology, Culture and Politics (James 2014).Another is the Seven Modalities model, in which the 7 pillars are Economy, Community, Occupational Groups, Government, Environment, Culture and Physiology (Thomas 2016). Resilience and long-term growth are common throughout all these modalities. For consistency, the 3-pillar model will be used when discussing sustainability.

II
INTERACTIONS BETWEEN LEAN AND SUSTAINABILITY

Lean practices have elements congruent with sustainability. There is a growing body of research evaluating the link between Lean practices (LP) and sustainability, most of this research has been conducted on the manufacturing sector. To provide a background on the current state of the link between LP and sustainability in the manufacturing sector, three systematic literature reviews were examined.

A systematic review was performed on the interrelationships between LP and Sustainability. The following is a summarization of relevant findings (Martínez León and Calvo-Amodio 2017). In the review performed by Martinez Leon et al, studies have shown that LP generally has positive effects on the social aspect of sustainability. LP are in part driven by the inclusive problem solving that includes lower level workers, as opposed to typical top down problem solving and policy implementation. This has been shown to lead to higher levels of employee engagement and intrinsic motivation. Specific implementations, such as Value Stream Mapping (VSM) have been shown to improve working conditions and are achieved through worker engagement.

The reduction of waste as a result from LP is the primary environmental benefit. Additionally, closer supplier relationships encourage information sharing; which can limit overproduction and excess transportation and storage; all of which have environmental impacts. Not only does LP facilitate sustainability, but when a company has sustainable practices, the workforce is more likely to adopt LP. This shows the synergistic effects of co-implementation of LP and sustainability.

II
INTERACTIONS BETWEEN LEAN AND SUSTAINABILITY

The tools use in LM can be modified to specifically account for resource utilization and waste production. Several groups have made changes to Value Stream Mapping to give it more of a sustainable focus. A VSM modified to include sustainability, denoted as Sus-VSM also accounts for raw material usage, energy consumption and water usage. There has also been an environmentally focused VSM, eVSM, which identifies the seven environmental wastes: energy, water, materials, garbage, transportation, emission, and biodiversity. Like VSM, Waste Flow Mapping (WFM) is a tool used to identify improvement opportunities in material and waste handling.

These sustainably modified VSMs have been implemented in both the manufacturing and construction industry. These have shown positive effects on environmental performance. The co-implementation of Lean and Sustainability goals reduces the tradeoff mentality.

Through this literature review, Martinez Leon et al have evaluated studies that cast doubt on the positive impacts of LP on manufacturing. A survey of 17 manufacturing plays suggested that plants with LP have higher volatile organic compound emissions than non-LP plants. Smaller lot sizes which are associated with Single Minute Exchange of Die (SMED), an LP technique, can result in more frequent deliveries and more emissions. This is one of the typical tradeoffs inherent to Lean and Sustainable initiatives. The tradeoff in choosing batch sizing and delivery frequency can be mitigated in other areas through waste reduction.

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Tasdemir and Gazo performed a literature review on articles addressing the intersection of Lean manufacturing, supply chain management, and sustainability. Over time, the scope of Lean, which initially was focused on operations within a company, has expanded to include the supply chain (Tasdemir and Gazo 2018).

Some businesses are further expanding the scope of Lean to include sustainability. The literature review performed by Tasdemir and Gazo found the following synergies and divergences between Lean and Sustainable concepts. The identified areas of synergies include a quality focus, versatility, organizational culture, key competencies and supply chain integration, key performance indicators (Tasdemir and Gazo 2018).

Quality is an important property to both Lean and Sustainable goals, it has a positive impact on the Triple Bottom Line (TBL). A versatile management and workforce can adapt to newly implemented Lean and Sustainable goals, a change-based mindset lowers the company's internal barriers to change implementation. Collaboration within the supply chain establishes information flow and reduces adversarial relationships, both of which are important to Lean and Sustainable goals. Key performance indicators (KPIs) can be shared between Lean and Sustainability. By selecting performance measures that impact both Lean and Sustainability, a coherent goal within the company can be constantly endeavored towards (Tasdemir and Gazo 2018).

Key areas of divergence are value creation constructs, types of waste, deployment strategies, tools, and methods. There is a divergence on value creation constructs between Lean and Sustainability. From a Lean point of view, the value only matters if the customer is willing to pay for the activity in question. The value focus of sustainability is based on the balance of the TBL impact. Waste elimination is defined differently between Lean and Sustainability; Lean is concerned with the economic impact of waste, and sustainability is concerned with the environmental impact of waste. There are differing tools and methods used for Lean and Sustainable goal achievement, this is an ongoing area of integration (Tasdemir and Gazo 2018).

In their review, Tasdemir and Gazo have identified efforts underway to mitigate the divergences between the two concepts. By modifying VSM to have a sustainable focus, Sus-VSM, workflow and sustainability goals can be aligned and improved. The EPA has released several methods to unite these divergences, such as: “The Lean and Green SCM Framework” with guidelines to reduce cost factors while improving environmental performance (Tasdemir and Gazo 2018).

This literature review also identified performance indices that have been created to align Lean and Sustainable goals, such as the Logistics Performance Index (LPI) and the Environmental Performance Index (EPI). Both indices have the drawback of not including the social pillar of sustainability. Many frameworks have been proposed, and may be useful for benchmarking purposes, but this is an ongoing area of research and implementation that is far from being well elucidated (Tasdemir and Gazo 2018).

II
INTERACTIONS BETWEEN LEAN AND SUSTAINABILITY

This systematic review done by Siegel et al looked at challenges and tools used to achieve LP and sustainability, in small and medium sized enterprises (fewer than 250 employees). Most common challenge to integration of LP-Sustainable practices is the lack of metrics and measurements. The most used tool is 5S, used in almost 80% of industries. There were 13 articles screened, only 6 listed green tools in addition to Lean tools, indicating companies are relying on Lean tools to achieve sustainability (Siegel et al. 2019).

Factors that lead to successful integration of LP and sustainability were also evaluated. Every paper screened listed employee involvement as a factor to success. Second to employee involvement was support of management, followed by established measurements and metrics. Most frameworks integrating LP and sustainability lack the measurement of the social aspect of sustainability (Siegel et al. 2019).

III
CURRENT STATE OF SUSTAINABILITY IN CONSTRUCTION

The demand for improved sustainability in buildings has vastly increased over the past 5 years. The amount of companies that had their over half their building projects certified green more than doubled from 2016 to 2018 (Dixon 2020). In the US, companies with most of their projects being "green" is expected to increase from 32% to 45% from 2018 to 2021. This is being driven more by client demands than by environmental regulation. The top 5 reasons behind the client demand for sustainable buildings are to: reduce energy consumption, protect natural resources, reduce water consumption, low emissions, and improve indoor air quality (Dodge Data & Analytics 2018).

There are three main methods for assessing sustainable construction practices, the Lawson method, the Twin model, and the LEED model. Sattary reviewed these in relation to existing construction practices and proposed criteria to be considered (Sattary 2004). The Lawson method is performed in two stages: the materials and the whole building assessment. It considers Life Cycle Assessment (LCA) but has little focus on the environmental impact of the construction process. The Twin model is a method for analyzing the life cycle of building products. The main criteria are "eco-toxicity" and "human toxicity", with a focus on related health issues. LEED is a green building rating system based on established and innovative criteria. The LEED scope is in three main areas, building monitoring and evaluation, building energy analysis and energy audits. All three methods assess environmental impact of the building life cycle; however, the impacts of the construction process receive comparatively less attention (Sattary 2004).

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Table 3.1 Construction-Sustainability Assessment Methods

Stage	**Category**	**Assessment method**
Pre-construction	Strategies, design	Twin, LEED
Pre-construction	Materials and product assessment	Lawson, LEED
During construction	Construction process	LEED
Post-construction	Whole building assessment	Lawson, Twin, LEED
Post-construction	Post occupancy assessment	Twin, LEED
Post-demolition	After demolition	LEED

Sattary proposed a checklist of areas to evaluate in the construction process:

- Policy (effective control)
- Site sensitivity
- Use of low ecological impact materials in process
- Use of recyclable, reusable onsite facilities
- Operational energy performance
- Equipment and type of machinery needed to perform
- Resource types (labor, human, facilities, materials)
- Water consumption and water waste
- Material waste in work and rework, daily inventory
- Effect on health, site security, safety, and noise control

Sustainability during the construction phase was assessed by O’Connor et al.

They assessed waste management, materials management, and project site energy management during the construction phase. From a review of the literature, the team developed a catalog of 54 Construction Phase Sustainability Actions (CPSAs). These are statements such as "Inspection and maintenance of construction equipment" and "promotion of local employment and skills development" (O'Connor, Torres, and Woo 2016).

Findings of CPSA implementation:

- 48/54 can improve environmental performance
- 37/54 can improve social performance
- 20/54 can improve economic performance
- 15/54 can increase both safety and schedule performance
- 7/54 can increase quality performance

Barriers to implementing CPSAs

- 36/54 are not implemented due to lack of information
- 27/54 are not implemented due to limited project resources
- 22/54 are not implemented due to outside owner/contractor control
- 16/54 are not implemented due to lack of infrastructure
- 7/54 are not implemented due to unfavorable site/project conditions

The CPSA catalog was developed to assess and provide construction-phase sustainability guidance. This research identifies actions that can contribute to sustainability in the construction phase (O'Connor, Torres, and Woo 2016).

Sustainable Project Planning (SPP) was evaluated by Yu et al across many industries, energy, civil engineering, hydroelectric, petrochemical, transportation, and others. 39 statements were given to project managers. Project managers were asked to state on a scale of 1-5 how strongly they agree with how much success of the project depends upon the statement. An Exploratory Factor Analysis (EFA) was performed, and 14 statements emerged as being significant to the success of a project. These 14 statements were then grouped into three factors (Yu et al. 2018):

Factor 1 – Managerial Control

1. Our project plan includes managerial control measures for project implementation
2. We implement the project task in accordance with the managerial control measures setting in the project plan
3. Project planning deliverables were used by the project manager to control team members sustainably
4. Project quality management was implemented sustainably based on the project plan
5. We track and monitor project progress effectively according to project plan

Factor 2 – Risk Response

6. Project potential risks were identified during project planning process
7. Our project planning deliverables contain the evaluation results for potential risks
8. Solutions for potential risks will be exported after project planning process
9. We usually avoid the potential risk proactively during the project planning process
10. We can respond to the risk emerging from the project implementation process effectively

Factor 3 – Work Consensus

11. Project teams will jointly decompose project activities during project planning process
12. Our project members always negotiate with the conflicting issues of the project plan together
13. Our team members acknowledge project's baseline plan unanimously
14. We will follow the steps from predetermined project plan to implement the project sustainably

This research shows that integrating sustainability into the project planning cycle makes an effectively sustainable project more likely (Yu et al. 2018).

The attitudes towards sustainability in the Chinese construction industry was evaluated by Chang et al. They surveyed companies' attitudes towards 29 Critical

Sustainability Aspects (CSAs). These CSAs were divided into the three categories of sustainability. The four highest of each category are as follows (Chang et al. 2018):

The highest-ranking aspects of the economic category are:

- Quality management, at number 1 overall
- Customer service, at number 2 overall
- Risk management, at number 3 overall
- Corporate strategy, at number 4 overall

The highest-ranking aspects of the social category are:

- Obeying laws and regulations, at number 5 overall.
- Occupational health and safety, at number 6 overall
- Wages and welfare, at number 7 overall
- Promoting development of the industry, number 11 overall

The highest-ranking aspects of the environmental category are:

- Construction waste management, at number 8 overall
- Land use efficiency, at number 9 overall
- Noise control, at number 10 overall
- Water conservation and harvesting; and Material conservation, tied at number 12 overall

Spots 1-4 are part of the economic category. The next highest-ranking category is the social aspect of sustainability, with spots 5-7 and 11. The lowest category of importance is the environmental category, with spots 8-10 and 12(Chang et al. 2018).

Most of these customer demands could also be met by reducing the impact of the process. Building Information Modeling (BIM) is a transformative technology that allows for collaboration and interaction amongst stakeholders. Most firms are using paper-based systems, which are less likely to recognize clashes and are more time and effort intensive. An implementation of BIM can impact all aspects of the triple bottom line. Social sustainability is achieved by allowing all stakeholders to have near real time input on every step of the design process, historically a very fragmented process. Economic sustainability is achieved through an average of 6.9% cost savings. Environmental sustainability is achieved through supporting building spatial design and analyzing the building's potential ecosystem. There are newer BIM technologies with a focus on the environmental factor, these BIMs have been dubbed "Green BIM" (Zhabrinna et al. 2018).

Saieg et al performed a systematic literature review on the interactions between BIM, Lean and sustainability in the construction industry. Their investigation at the time stated that there was no study that simultaneously researched BIM, lean and green development. The findings were that there is a large unexploited potential for both operational and technological improvements (Saieg et al. 2018).

There is a parallel adoption rate between BIM technologies and lean management practices as one increases the other also increases. This indicates that BIM can facilitate lean construction practices, and that lean principles have parallels with BIM tools. In using BIM throughout the project life cycle stakeholders can enforce system sustainability with continual audits and calculations against alternatives. Assessments of design alternatives in differing conditions regarding eco-efficiency and energy performance can happen as change controls are considered (Saieg et al. 2018).

The lack of research on the integration of BIM, lean and green; but a small body of research on all iterations of each of 2 of the 3 concepts mentioned indicates that there is significant unrealized potential to be had. The authors expect a greater investment in proactive solutions and innovative methods regarding lean, BIM, and green construction (Saieg et al. 2018).

The efficient use of resources depends upon many factors in the construction process, these are chiefly: design decisions, material selection, waste recycling and re-use, energy use, and emissions during the whole life cycle of a project. This project life cycle includes the supply chain, the construction process, the resource management, and the building performance. There are emerging resource management strategies for use of construction by-products. One such strategy would be to use slag, fly ash and ash from timber to supplement concrete production, effectively lowering the emissions produced and the energy required to produce concrete (Sfakianaki 2015).

There is research being done to limit the geotechnical construction impact. Chu reviewed several emerging technologies that limit the environmental impact of construction. One is the use of biocement as an alternative to Portland cement. Biocement uses microbial processes to induce calcium carbonate crystals into the soil, increasing the soil shear strength. Biocement is still in the experimental stage but is being rapidly scaled from laboratory to industrial process level (Sfakianaki 2015).

Another emerging geotechnical technology is bio-desaturation for mitigation of liquefaction hazards. When an earthquake occurs, the soil acts as a liquid and loses a portion of its bearing capacity. Current mitigation techniques involve soil modification using cement. By replacing 5% of the water in soil with gas, liquefaction resistance in sand is doubled. With introduction of biogas producing microorganisms, gas displaces the water in a cost-effective manner and less cement is needed (Sfakianaki 2015).

An emerging technology is the use of plastic waste to make construction products. Polypropylene can be melted and mixed with soil and used to make bricks or cylinders. This yields a lightweight material with a high compressive strength (Sfakianaki 2015).

These technologies presented are not yet a viable economic alternative, but as research progresses and the processes are scaled up, they become a more attractive economic alternative in addition to their lessened environmental impacts.

IV
CURRENT STATE OF LEAN IN CONSTRUCTION

The current condition of Lean Construction was evaluated at small and medium enterprises (SMEs) in highway construction by Tezel et al. They surveyed 20 companies about their Lean engagement at various stages: Project Delivery, Process, Training, Project Governance and Supply Chain. The five most agreed upon statements were (Tezel, Koskela, and Aziz 2018):

1. "SME's current inability to affect the design phase".
2. "The focus of HE (Highways England) being on Tier 1s and large Tier 2s for LC"
3. "SMEs already doing some process-based improvements even though not labelled "LC""
4. "Lack of in-house LC training mechanisms at SMEs"
5. "the limited use of BIM as an enabler for LC and information flow"

The five least agreed upon statements were:

6. "a haste in the current LC implementations"
7. "lack of resources for LC at SMEs"
8. "risk aversion being too high for LC in the supply chain"
9. "lack of top management support"
10. "LC being pushed from top without much understanding"

The "Supply Chain" section of the questionnaire was the section with the most negative responses. SMEs stated they little engagement with the client and had little chance to participate in the design phase (Tezel, Koskela, and Aziz 2018).

Ogunbiyi et al studied the effects of lean construction techniques on sustainable construction. Based on their literature review, they assert that crews that practice lean principles have 45% lower accident rate. Standardizing processes, continual improvement, improved process flow likely contribute to this lower accident rate (Ogunbiyi, Goulding, and Oladapo 2014).

IV
CURRENT STATE OF LEAN IN CONSTRUCTION

Freitag et al performed a literature review on the integration of concepts about lean construction, sustainability, and life cycle of buildings. As of their literature review performed in 2016, there were only 8 published studies that met their criteria, indicating that the research is in its nascency. Through the review, a theoretical framework was developed to integrate the concepts of lean construction, sustainability and building life cycle. The framework identified broke the life cycle into 5 phases (Besser Freitag et al. 2017):

1. Define goals: stakeholders state their goals
2. Development: planning, design, scheduling
3. Construction: physical materialization of project
4. Use: operation and maintenance of building
5. Deconstruction: disposal and recycling of building

Most of the applicable research on the contributions of lean construction are related to the development and construction steps during the building life cycle. There were virtually no contributions to the deconstruction phase, and only two contributions at the use stage (Besser Freitag et al. 2017).

Khaba and Bhar looked at the key barriers to implementing Lean Construction using Interpretive Structural Modeling (ISM). ISM identifies relationships among factors surrounding an issue by identifying cross reactivity and develops a hierarchy in which identifies factors with the most influence over other factors. Of the 13 barriers analyzed, no barrier was found to be autonomous, meaning a change to one barrier had an impact on the performance of the others (Khaba and Bhar 2017).

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The most dependent barriers were resistant to change, lack of performance measurement systems, lack of technical capabilities, and lack of green initiatives. The least dependent barriers which drove the dependence of other barriers were Lack of understanding of customer needs, Cultural differences, Inconsistency in Government Support, and Project Subcontracting (Khaba and Bhar 2017).

The following factors are considered "Linkage Barriers" and connect the driving barriers to the dependent barriers: Not recognizing financial advantage, Lack of awareness and understanding of Lean Construction, Financial Constraints, Lack of planning for quality, Lack of lean consultants and trainers (Khaba and Bhar 2017).

These results suggest that a stronger integration of other stakeholders such as the supply chain, the subcontractors, and the customer would increase the driving power of two of the significant barriers, Project subcontracting and Lack of understanding of customer needs. Cultural differences and Governmental support are less likely to be immediately impacted at the company level. Once a stronger integration of stakeholders is achieved, addressing the linkage barriers will have amplified downstream effects on the dependent barriers (Khaba and Bhar 2017).

Zhang et al studied the factors impacting workflow reliability. They identified critical factors based on the current state of literature regarding construction workflow and used and applied a Structural Equation Model (SEM) to determine interrelationships. There were 19 factors found to be critical, of these 19 factors, 5 were found to have a direct positive impact on workflow reliability. These 5 factors are: labor resource stability, managerial level support of each part in the project, visualization of workflow and rework and weather (ZHANG, CHEN, and SUO 2017).

The path coefficient between the critical factors with the highest effect was from labor loyalty to labor stability to workflow reliability. This suggests improving labor loyalty would improve labor stability, which would have the greatest impact on workflow reliability (ZHANG, CHEN, and SUO 2017).

Most of the work performed in the construction industry is done by subcontractors. Given that subcontractors typically have their own management structure, this presents an additional consideration for lean construction. Yin et al studied the traditional subcontracting procurement process and evaluated lean principles and how they may impact the entire operation. The financial success of a construction project is closely related to the procurement process. The traditional subcontracting procurement process is based upon price competition. Typically, subcontractors are not fully aware of the operational sequence of the project and have trouble integrating into the workflow. Collaboration amongst stakeholders and a standardized process can limit waste (Yin et al. 2014).

Yin et al identified seven critical factors that correspond to seven types of waste. These seven critical factors necessary to the lean out the subcontracting workflow: Quality Arrangement, Quantity Arrangement, Time Arrangement, Inventory Place Arrangement, Arrangement of Task Number and Order, Path Arrangement and Location Arrangement (Yin et al. 2014).

- Quality arrangement reduces waste from defects, by having the correct specifications entering the site, secondary reprocessing is reduced.
- Quantity arrangement reduces overproduction, input materials are not excessive to take up extra space, or too few that work is limited.
- Time arrangement reduces delays, resources entering the site are on time as to not hold up work.
- Inventory Place Arrangement reduces waste by limiting moving around excess inventory.
- Arrangement of task number and order reduces waste by limiting unnecessary processing
- Path arrangement reduces waste by specifying fixed transport paths on the site.
- Location arrangement reduces waste by limiting unnecessary movement of people and equipment

In a case study observed by Yin et al, a steel decking company implemented a standardized process based upon the seven arrangements. The critical path went from 10 days to 8.5 days, idle time spent waiting was reduced by 10%, total cost was reduced by 16.4% (Yin et al. 2014).

Use of lean principles has facilitated by increasing the utilization of Internet of Things (IoT). Dave et al evaluated how IoT communication standards effect the information flow over the lifecycle of a construction project. Lookahead planning, also known as medium term planning, has been argued to be one of the most difficult aspects to implement. This is because there is traditionally no software system or mechanism to track or anticipate constraints on workflow reliability before execution. Information integration is low across the industry, with 1.3% of companies claiming full systems information integration across the supply chain, and only 12.7% claiming full integration internally. 32.9% of companies claimed partial relayed integration, meaning non-integrated software programs are used, and 17.7% claimed no integration (Dave et al. 2016).

IV
CURRENT STATE OF LEAN IN CONSTRUCTION

Dave et al researched IoT standards and how they contribute to leverage a lean construction management system. The following components are needed in an IoT system: Production planning and control of workflow, Process and product integration, Visual controls, and information in production. To do this, the system needs to interface with RFID systems, phones, USB input from equipment, etc. This sort of integration would help to close the loop between the head office and the field. They acknowledge that addressing the information flow in a construction site is a complex issue that relies on a variety of factors; but that the IoT standards align with lean principles within the construction industry (Dave et al. 2016).

There is a concept in lean called "The Obeya Room". Obeya is a Japanese word meaning "large room" and was first implemented by a Toyota executive to facilitate large engineering projects. Many sheets of paper were hung up around a large room, each one representing a different stakeholder in the project. This was a way to facilitate collaboration and allow others to see how the other stakeholders have opinions and require and information flow. BIM acts as a digital Obeya room (DOR) to facilitate information flow and collaboration amongst stakeholders (NASCIMENTO et al. 2017).

Nascimento et al studied the synergies between lean and BIM by assessing the impact of a DOR framework and the PDCA (Plan Do Check Act) cycle. They assessed welds that were made in the field vs prefabricated, as welds made in the field take 4x the time as those that are prefabricated. They found that in construction projects that used DOR and the PDCA cycle, 8.7% less time was spent welding than with traditional management principles (NASCIMENTO et al. 2017).

Alvarenga et al examined the evolving relationship between BIM and Lean construction in Brazil. They surveyed undergraduate university professors as to whether lean construction was taught, and all reported teaching lean construction philosophies. When asked to rate the subjective, relative amount of lean construction teaching, the professors reported teaching at a level of 1.75 out of 5. When the professors were asked about the efficacy of lean construction, they rated it an average of 3.5 out of 5. This is a large disconnect between the perceived importance and current level of education (Alvarenga et al. 2017).

When asked if BIM was taught at universities, 100% of professors responded yes. When asked to rate the level of BIM education at universities, they rated it as an average of 1.2 out of 5. When asked about the relative importance of BIM, the university professors rated it an average of 4.55 out of 5. This is yet another disconnect between the teaching level and perceived importance (Alvarenga et al. 2017).

When asked about the benefits to BIM, the top response, chosen by 69% of respondents, was "Integrated collaboration of all parties involved in the project". When asked about the main obstacles to teaching BIM, the top chosen response, with 60% of respondents selecting, was "Professor's low technical knowledge of the matter". This shows that professors believe BIM is important to facilitating lean construction, as collaboration is integral to lean philosophies, but that the lack knowledge to teach the key information (Alvarenga et al. 2017).

V
CASE STUDIES AND MODELING

Waste management is typically implemented after waste is created, rather than attempting to reduce the creation of waste. Waste prevention measures are dependent on stakeholders; from design, construction, building lifecycle, and deconstruction (Ajayi et al 2017). The largest percentage of C&D waste is caused by activities at the pre-construction stages. Only 2% of construction companies hold waste management meetings, and only 32% had waste management goals (Osmani et al 2008).

The existing waste management tools such as NETWaste, DOWT-B, and SMARTWaste have not been shown to be helpful in the design process (Osmani et al 2008). Waste is produced throughout the building lifecycle, making lifecycle analysis an important factor in C&D management. No existing C&D tool has functionality for lifecycle analysis (Akinade et al 2018).

The ineffectiveness of current tools and management strategies can be mitigated by Lean principle implementation. Previous claims have argued that designing for waste minimization can reduce waste by 33% (Alarcon 2019), or by 30-50% and cost reduced by 5-10% (Pampanelli et al 2014). Four case studies on Lean implementation effects on waste have been performed.

Ajayi et al performed a case study where construction was waste efficient. This was coordinated through BIM to prevent design clash and produce error free documentation and document clarity. The average waste generated is 14.7 tons per 100,000 euros spent. After implementation of waste minimization strategies, the case study resulted in 5.7 tons per 100,000 euros spent. This is a 65% reduction in waste. While this is extreme and potentially an outlier, it does provide evidence that designing for waste minimization can reduce waste by 33% (Ajayi et al 2017).

Belayutham et al studied they interplay between administrative processes and production processes on a construction site. Lean principles were applied to the administrative processes and impacts on time and the environmental factor were measured. After applying lean principles, lead time was reduced by 37%, total process time was reduced by 34%, and there was a 17% reduction in environmental impact factor (Belayutham et al 2016).

Nowotarski et al studied the impacts of waste reduction by lean construction. A cluster of 5 office buildings were being constructed, for the crew at two of the buildings, lean principles were applied to the construction process. Brick laying waste went from 6.2% of material wasted to 3.4%, about a 45% reduction in waste (Nowotarski et al 2019).

A second case study was performed by Belayutham, this time on the efficacy of lean principles on an earthwork operation. They measured the impacts on time, cost, and the environmental factor. Time was reduced by 43%, cost reduced by 25% and environmental factor reduced by 42% (Belayutham et al 2017).

Table 5.1 Studied Lean Impacts on Construction

Study	Material Waste	Time	Env Factor	Cost
Ajayi	-65%	N/A	N/A	N/A
Belayutham	N/A	-34%	-17%	N/A
Nowotarski	-45%	N/A	N/A	N/A
Belayutham	N/A	-43%	-42%	-25%

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To account for the fact that there is very little data, and that the case studies may be outliers, a modifier of 0.5 will be applied to all measured outcomes. This assures a more conservative model. Lean impacts with modifier for model are tabulated in Table 5.2. EPA C&D data is tabulated in Table 5.3.

Table 5.2 Lean Impacts on Construction

Measured Category	Raw factors	Average	With 0.5 modifier
Material Waste	-.65 and -.45	-.55	-.27
Time	-.34 and -.43	-.38	-.19
Env Factor	-.17 and -.43	-.3	-.15
Cost	-.25	-.25	-.12

Table 5.3 EPA C&D data

	Construction Waste	**Demolition Debris**	**Next Use**	**Landfilled**
Material	million tons (MT)	million tons (MT)	million tons (MT)	million tons (MT)
Concrete	24.2	381	334	71.1
Wood	3.4	37.4	11.2	29.6
Drywall and Plasters	3.9	11.3	2.1	13.2
Steel	0	4.7	3.6	1.1
Brick and Clay Tile	0.3	12	1.5	10.8
Asphalt shingles	1.2	13.9	2.1	13
Asphalt concrete	0	107	102.1	4.9
Total	33	567.3	456.6	143.7

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CASE STUDIES AND MODELING

33 million tons of construction waste was generated in 2018 in the United States. Through implementation of lean principles, this waste could be reduced by 8.9 million tons. It is important to note that construction accounts for 5.5% of the C&D debris generated. It is likely that a similar portion of waste would be reduced from the demolition portion, but no studies have been done on lean impacts on the deconstruction process. Further study is needed to develop a more sophisticated model on lean principles on waste reduction.

By compiling these case studies and applying a conservative multiplier, this model shows that lean principle implementation during the construction phase can reasonably reduce material waste by 27%. This can be accomplished by also reducing the time to completion by 19%, the environmental impact by 15%, and the cost by 12%.

VI
STATE OF THE INDUSTRY IN SE WISCONSIN

In SE Wisconsin nine project managers responded to an email survey about the use of Lean and sustainability. 5 questions were asked (Waite, n.d.):

Fig 6.1 Q1: Use of Lean Principles

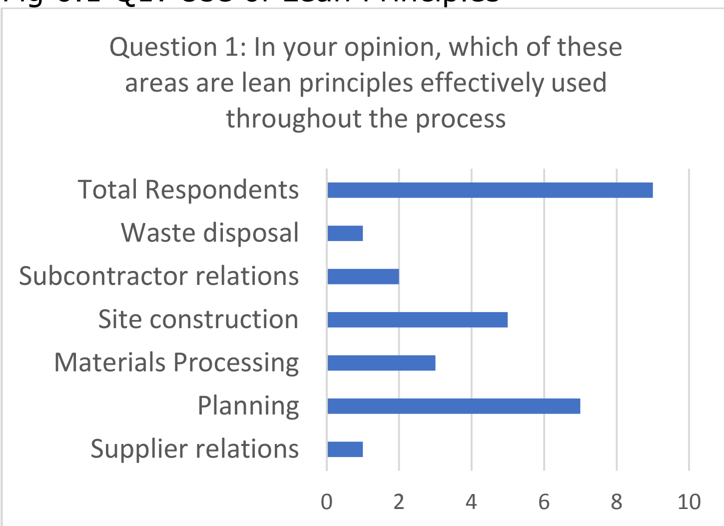


Fig 6.2 Q2: Use of Lean Tools

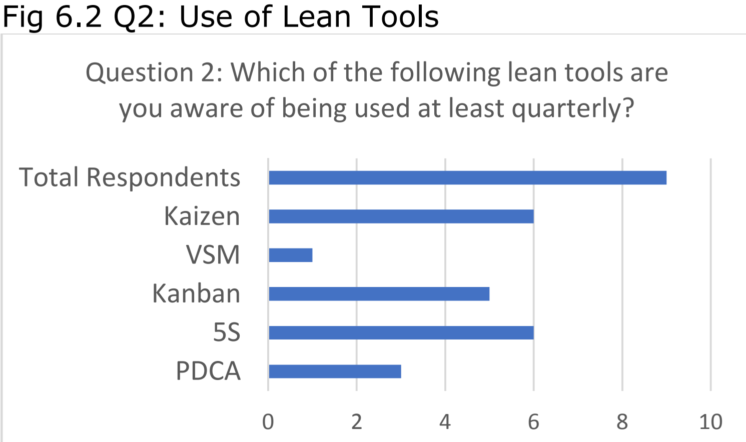


Fig 6.3 Q3: Use of Lean for Sustainability

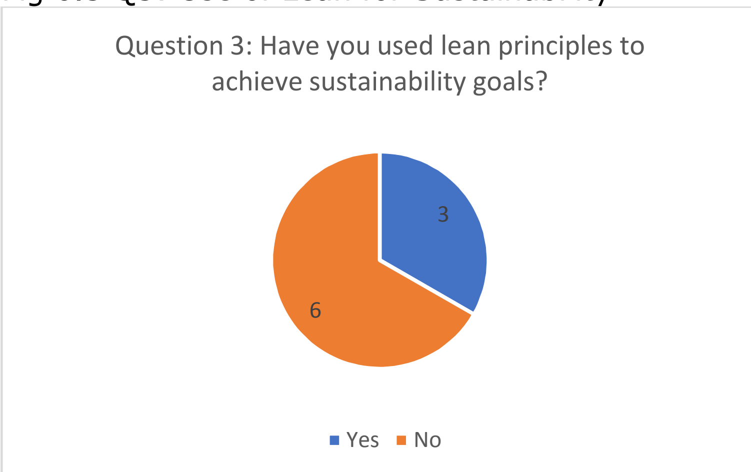


Fig 6.4 Q4: Use of Lean for Productivity

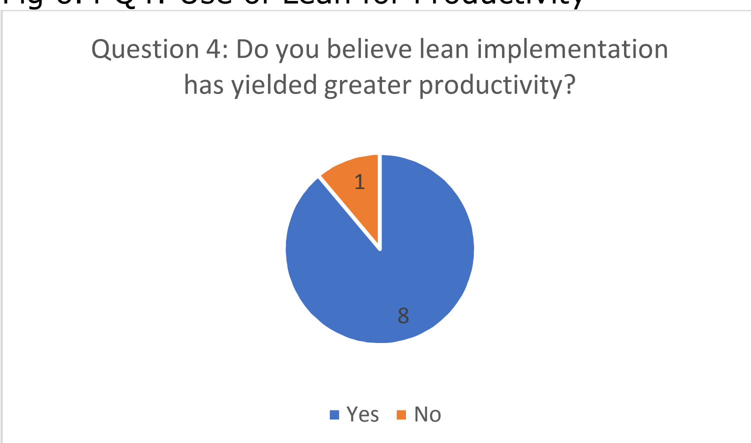
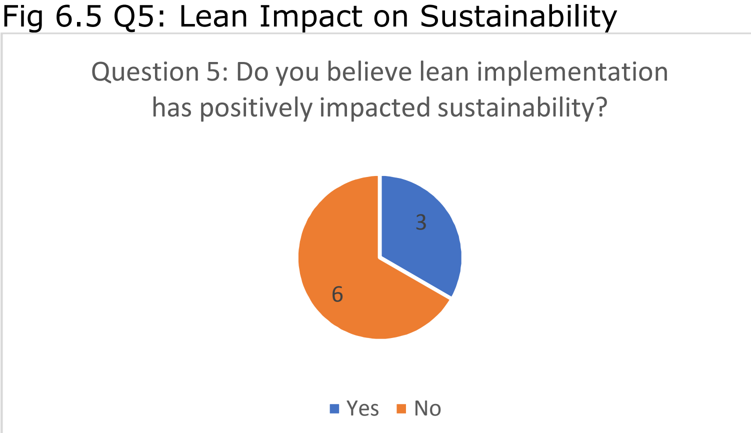


Fig 6.5 Q5: Lean Impact on Sustainability



VII
DISCUSSION AND PROPOSED FRAMEWORK

Lean management philosophies have several elements aligned with sustainability. Application of Lean practices, without modification specific to sustainability, generally results in positive impacts on the social pillar. This occurs through higher levels of employee engagement, closer supplier relationships and information sharing across stakeholders. Secondary to the positive social impact, is the waste reduction. Waste reduction because of Lean management philosophies occurs less reliably, although it does tend to have a positive impact (Martínez León and Calvo-Amodio 2017).

Lean philosophies place focus on several aspects critical to sustainability, but not on other key aspects. There are efforts underway to create new tools and methods that will mitigate these areas Lean does not have a focus on. The main challenges to integrating Lean and Sustainability are the tools available, the employee involvement, and support of management. As the tools become more sophisticated, and Lean-sustainability education across the company improves; these challenges will lessen (Tasdemir and Gazo 2018).

To meet client demands for sustainable buildings, there are several rating systems. These ratings systems focus more on the performance of the building than on the construction process (Sattary 2004).

There has been recent research in sustainability during the construction phase (O'Connor, Torres, and Woo 2016), research into sustainable project planning across multiple industries (Yu et al. 2018), and research into industry professionals' attitudes towards sustainability (Chang et al. 2018). The steadily growing body of research can be used to develop a framework for a sustainable project planning and construction.

BIM (Building Information Modeling) is an increasingly used technology that enables both Lean and sustainable goals. BIM and Lean have been noted to have a cyclic adoption influence, the adoption of either BIM or Lean makes the adoption of the other more likely. This is most likely due to the utility of BIM in Lean management (Saieg et al. 2018). Use of BIM increases collaboration, thereby impacting the social pillar. BIM tends to result in cost savings, positively effecting the economic pillar. BIM positively impacts the environmental pillar by analyzing the building's ecosystem. There is more sophisticated BIM software that has a focus on the environmental factor, nicknamed "Green BIM" (Zhabrinna et al. 2018). There was no available research on the integration of BIM, Lean and sustainability, but research on each iteration of 2 out of the 3. There is likely unrealized potential in the synthesis of these concepts (Saieg et al. 2018).

There are technological advances being made to achieve sustainable construction practices. Among these are use of construction by-products being recycled into the raw material resources being used. Emerging geotechnical technologies such as biocement and bio-desaturation are currently being explored. These technologies are not yet a viable economic alternative (Sfakianaki 2015).

The case studies available strengthen the argument that implementation of Lean principles can facilitate sustainability while improving productivity. Case studies have only been performed on the construction phase, not on the deconstruction phase. More waste is generated at the deconstruction phase. While it is likely that Lean principle inclusion would reduce waste at the deconstruction phase, more research is needed to confirm this. An aggregation of 4 case studies on Lean construction conservatively found that material waste can be reduced by 27%, time for project completion can be reduce by 19%, environmental impacts can be reduced by 15%, and cost can be reduced by 12%. This would correspond to 8.9 million tons of waste not being generated in 2018. This also means that 27% of waste during the construction phase is produced due to administrative inefficiencies.

When surveyed about the state of Lean in construction, the most agreed upon statements generally indicate a lack of coherent and complete standardized in-house processes for Lean practices. The most negative responses were regarding the supply chain, indicating currently there is a lack of collaboration amongst stakeholders (Tezel, Koskela, and Aziz 2018).

There is very little published literature on Lean construction, sustainability, and life cycle of buildings. From what is available, a rough framework was able to be developed:

1. Define goals: stakeholders state their goals
2. Development: planning, design, scheduling
3. Construction: physical materialization of project
4. Use: operation and maintenance of building
5. Deconstruction: disposal and recycling of building

Most studies were related to the development and construction phase. There were no published studies on the deconstruction phase, and only two studies on the use phase. Further study is needed on the interrelationships between lean construction and the impacts on building use, and lean construction impacts on deconstruction (Besser Freitag et al. 2017).

Most of the work in construction is performed through subcontracting. Given that subcontractors have their own management structures, this presents an additional issue in implementing Lean philosophies. An in-house standardized process to procuring subcontractors can help to mitigate these issues (Yin et al. 2014).

When analyzing barriers to implementing Lean construction were analyzed, the barriers in which others were relying on were "Lack of understanding of customer needs", "Cultural differences", "Inconsistency in Government support", and "Project Subcontracting". This agrees with Tezel's findings in that collaboration, specifically with subcontractors is a lacking within the project structure (Tezel, Koskela, and Aziz 2018). Tezel et al's findings that a lack of in-house Lean process likely agrees that Khaba and Bhar's findings that the company's culture is a common barrier to Lean adoption (Khaba and Bhar 2017).

Increased technological adoption in the construction industry has enabled the adoption of Lean principles. IoT (Internet of Things) facilitates information flow by integrating and automating information flow from equipment and sensors (Dave et al. 2016). The use of BIM facilitates Lean practices to promote information flow and collaboration (NASCIMENTO et al. 2017).

The increasing importance of BIM and Lean necessitates education into their applications. When surveyed, university professors are aware of the importance of both BIM and Lean, but then rate the level of education in them relatively low

(Alvarenga et al. 2017). This disconnect in education and importance agrees with the challenges found in implementing Lean in construction by Leon and Calvo-Amodio in "Towards lean for sustainability..." (Martínez León and Calvo-Amodio 2017).

The data obtained from SE Wisconsin generally agree with previous findings. Project managers believe that implementation of lean principles yield greater productivity, but most have not used lean principles to achieve sustainability goals, and most do not believe lean has positively impacted sustainability (Waite, n.d.).

VII
DISCUSSION AND PROPOSED FRAMEWORK

Framework for Lean-Sustainability Integration

A lean management – sustainability framework for waste reduction in construction could be implemented by following the policy framework put forth by UNSW. The development cycle is:

1. Identify and Scope
    a. Identify responsible personnel
    b. Identify need, objective, scope
2. Draft, develop, document, consult, finalize
3. Communicate, implement, and monitor feedback
4. Review

Part 1: Identify and Scope:

Identify responsible personnel, needs, objectives, and scope. Personnel with adequate knowledge, skills and abilities must be assigned to developing the procedures. These personnel should be familiar with lean and/or sustainability. The needs of the organization must be identified, as these will determine the objectives to target.

After the needs and objectives have been identified, the scope of the policy will be defined. This top down approach assures the policies being implemented align with the goals of the organization. Aligning efforts of policy changes with goals of the organization means that the tracked KPIs (Key Performance Indicators) will measure the efficacy of policy changes (Tasdemir and Gazo 2018).

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Part 2: Draft, develop, document, consult, finalize

The responsible personnel should develop a working group involving stakeholders in affected areas. The working group will draft documents, consult with affected personnel, and use the lean tool of "The Obeya Room" to achieve a finalized policy (NASCIMENTO et al. 2017).

Part 3: Communicate, Implement and Monitor Feedback

The working group should communicate the policy changes and provide education and training about how the new procedures align with company goals. The lean tool of a Kaizen event can be used to get feedback and increase engagement of affected personnel. After the changes have been communicated and implemented, the working group should monitor feedback as they relate to the objectives (Womack and Jones 1997).

Part 4: Review

Documents and policies should be reviewed on a regular (annual, semi-annual, etc) basis to ensure policies are up to date and meet company objectives. The lean tools of PDCA (Plan Do Check Act) and/or CIP (Continual Improvement Process) can help the working group to regularly make improvements based on feedback and key performance indicators (NASCIMENTO et al. 2017).

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Table 7.1 Stepwise Process for Policy Implementation

Step	**Explanation**	**Useful Tool**
Company Goal	Consult with upper level management on company goal	+ See below
KPI to track goal	Consult with upper level management on how goals are tracked	+ See below
Policy Scope	Define needs, objectives, and personnel	5S
Convene Working Group	Select stakeholders from affected areas	Obeya Room, BIM
Draft Policy	Align changes with company goals	5S
Educate and Communicate	Train and empower personnel	Kaizen event
Monitor Feedback	Solicit responses and gather data	CIP
Review	Make improvements based on feedback	PDCA

+ The company goals and KPIs typically are not under control of the project manager. These need to be defined by upper level management and communicated to the project managers. Without defined goals, tracked key performance indicators, and clear information flow: there is a lower chance of successful implementation.

As a hypothetical to illustrate the framework implementation, a construction company's goal may be to reduce waste generation that will end up in a landfill. To accomplish this goal, more waste will be diverted into recycling and reuse. The policy scope in this case will be the installation of recycling collection points, and material reuse points at several places on the job site; and to have personnel effectively educated on how they can help work towards the company goals.

To begin policy development, a working group will be established. The working group will consist of stakeholders in the project: personnel from management, functional job site personnel and other affected personnel. The working group would determine locations, educational methods, and draft documents.

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The working group would communicate and educate the affected personnel on the policy changes, through formal meetings, training events and by putting up clear signage near collection points. After policy implementation, waste stream auditing will occur to assess the policy effectiveness. The working group will solicit feedback regarding collection point location, education effectiveness and encourage ideas for improvement.

After a short implementation period, the working group will assess waste stream auditing results and personnel feedback to improve the process. Further changes may be made if needed. At regular intervals (yearly, semi-annual, etc.) the policies will be assessed against feedback and waste stream audit results to continually improve. The result of successful policy implementation that is aligned with company goals, that effectively educates and engages personnel, will result in positively trending KPI data.

Implementing a sustainable project using this framework will mitigate the most common Construction Phase Sustainability Action (CPSA) "Not Implemented Due to Lack of Information". This eliminates the waste resulting from poor information flow and projects not aligning with company goals (O'Connor, Torres, and Woo 2016).

Clear communication and receiving input from affected personnel can help to increase engagement. "Employee Involvement" was the most common factor listed in integrating Lean principles and sustainability (Siegel et al 2019). The path coefficient between factors critical to project success was "Labor Loyalty" to "Labor

Stability" to "Workflow Reliability" (ZHANG, CHEN, and SUO 2017). By engaging all personnel, labor loyalty is improved, and the project is more likely to become a success. Use of the Obeya Room, BIM, 5S, and Kaizen events engage personnel and facilitate information flow. Embedding lean tools into a sustainable project improves critical factors necessary for project success. The result is the reduction of waste and creation of value.

Implementing a project using this basic framework accomplishes 6 of 14 of the statements in Sustainable Project Planning, these are statements that if true about a project, make a sustainable project more likely to be successful (Yu et al. 2018).

- 1. Managerial control measures track success of project
- 2. Project implemented in accordance with managerial measures
- 5. Track and monitor progress according to project plan
- 6. Potential risks identified in project planning
- 9. Avoidance of potential risks during project planning
- 14. Follow steps from project plan to implement project sustainably

An intentional effort to include more of the SPP statements within the framework would make a successful project even more likely

VIII
CONCLUSION

Through adoption of Lean management principles, the construction industry can become more sustainable while increasing productivity. Due to the nascency of Lean being used for sustainability, the toolkits to address the key metrics are not fully developed, and the workforce does not have the knowledge to buy into the process. There is strong research, mostly in the manufacturing sector, indicating that Lean can effectively be used to positively impact sustainability. The research in the construction sector is in its very early stages.

The demand for sustainable building is growing steadily, being driven by client demands. To achieve the client's sustainable goals, a framework from project planning to building use will mitigate the tradeoff mentality of financial vs environmental impacts. There is some research to provide for a rough framework of collaboration through all stakeholders and tracking of key performance indicators. Further research will be needed to refine the framework into a well-defined process.

There were four applicable case studies to develop a model. The case studies do strengthen the idea that Lean implementation would increase both productivity and sustainability in the construction industry.

The significance of this work is that it shows the available case studies do agree with the theoretical research, but that research on the deconstruction phase is needed to develop a more sophisticated model. While more research is needed, the available research shows that there is room for the construction industry to grow in both productivity and sustainability.

IX
BIBLIOGRAPHY

"5S Success with Clarity 5S Cleaning Stations: Clarity Visual Management," October 14, 2020. https://www.clarityvisualmanagement.com/2018/06/20/5s-success-clarity-5s-cleaning-stations/.

Akinade, Olugbenga O., Lukumon O. Oyedele, Saheed O. Ajayi, Muhammad Bilal, Hafiz A. Alaka, Hakeem A. Owolabi, and Omolola O. Arawomo. "Designing out Construction Waste Using BIM Technology: Stakeholders' Expectations for Industry Deployment." Journal of Cleaner Production 180 (2018): 375–85. https://doi.org/10.1016/j.jclepro.2018.01.022.

Alarcón, Luis F. "Tools for the Identification and Reduction of Waste in Construction Projects." Lean Construction, n.d. https://doi.org/10.4324/9780203345825_tools_for_the_identification_and_reduction.

Alvarenga, Thomas, Edson Neves Da Silva, Carlos Luiz, Brasil, and Brito Mello. 2017. "BIM and Lean Construction: The Evolution Obstacle in the Brazilian Civil Construction Industry." *Technology & Applied Science Research* 7 (5): 1904–8.

Ajayi, Saheed O., Lukumon O. Oyedele, Olugbenga O. Akinade, Muhammad Bilal, Hafiz A. Alaka, Hakeem A. Owolabi, and Kabir O. Kadiri. "Attributes of Design for Construction Waste Minimization: A Case Study of Waste-to-Energy Project." Renewable and Sustainable Energy Reviews 73 (2017): 1333–41. https://doi.org/10.1016/j.rser.2017.01.084.

Belayutham, Sheila, Vicente A. González, and Tak Wing Yiu. "Clean–Lean Administrative Processes: a Case Study on Sediment Pollution during Construction." Journal of Cleaner Production 126 (2016): 134–47. https://doi.org/10.1016/j.jclepro.2016.02.091.

Belayutham, Sheila, Vicente A. González, and Tak Wing Yiu. "Lean-Based Clean Earthworks Operation." Journal of Cleaner Production 142 (2017): 2195–2208. https://doi.org/10.1016/j.jclepro.2016.11.060.

Besser Freitag, Alberto Eduardo, Rosley Anholon, Valmir Martins de Oliveira, and Tomás Vivanco Larrain. 2017. "Integration of Concepts about Lean Construction, Sustainability and Life Cycle of Buildings: A Literature Review." *Brazilian Journal of Operations & Production Management* 14 (4): 486. https://doi.org/10.14488/bjopm.2017.v14.n4.a5.

Chang, Rui-Dong, Jian Zuo, Zhen-Yu Zhao, Veronica Soebarto, Yujie Lu, George Zillante, and Xiao-Long Gan. 2018. "Sustainability Attitude and Performance of Construction

Enterprises: A China Study.” *Journal of Cleaner Production* 172 (January): 1440–51. https://doi.org/10.1016/j.jclepro.2017.10.277.

Dave, Bhargav, Sylvain Kubler, Kary Främling, and Lauri Koskela. 2016. “Opportunities for Enhanced Lean Construction Management Using Internet of Things Standards.” *Automation in Construction* 61 (January): 86–97. https://doi.org/10.1016/j.autcon.2015.10.009.

Dixon, Lucy. 2020. “Global Demand for Green Buildings Grows | Facilities Management | Construction Global.” Www.Constructionglobal.Com. February 17, 2020. https://www.constructionglobal.com/facilities-management/global-demand-for-green-buildings-grows.

Dodge Data & Analytics. 2018. “World Green Building Trends 2018.” https://www.worldgbc.org/sites/default/files/World%20Green%20Building%20Trends%202018%20SMR%20FINAL%2010-11.pdf.

EPA. n.d. “Sustainability Primer.” Https://Www.Epa.Gov/. Accessed October 15, 2020. https://www.epa.gov/sites/production/files/2015-05/documents/sustainability_primer_v9.pdf.

James, Paul. 2014. *Urban Sustainability in Theory and Practice*. Routledge. https://doi.org/10.4324/9781315765747.

Jsensi. “Student Affairs Consulting, Business Consulting & Training Services.” Campus Kaizen. Campus Kaizen, July 23, 2020. https://campuskaizen.com/kaizen/.

Karbassi, Lila. 2019. “Social Sustainability | UN Global Compact.” Unglobalcompact.Org. April 11, 2019. https://www.unglobalcompact.org/what-is-gc/our-work/social.

Khaba, Sorokhaibam, and Chandan Bhar. 2017. “Modeling the Key Barriers to Lean Construction Using Interpretive Structural Modeling.” *Journal of Modelling in Management* 12 (4): 652–70. https://doi.org/10.1108/jm2-07-2015-0052.

Martínez León, Hilda C., and Javier Calvo-Amodio. 2017. “Towards Lean for Sustainability: Understanding the Interrelationships between Lean and Sustainability from a Systems Thinking Perspective.” *Journal of Cleaner Production* 142 (January): 4384–4402. https://doi.org/10.1016/j.jclepro.2016.11.132.

McKinsey Global Institute. 2017. “Reinventing Construction: A Route to Higher Productivity.”

NASCIMENTO, Daniel Luiz de Mattos, Elisa Dominguez SOTELINO, Thiago Pires Santoloni LARA, Rodrigo Goyannes Gusmão CAIADO, and Paulo IVSON. 2017. “CONSTRUCTABILITY IN INDUSTRIAL PLANTS CONSTRUCTION: A BIM-LEAN APPROACH USING THE DIGITAL OBEYA ROOM FRAMEWORK.” *Journal of Civil*

Engineering and Management 23 (8): 1100–1108. https://doi.org/10.3846/13923730.2017.1385521.

Nowotarski, Piotr, Jerzy Paslawski, and Jedrzej Skwarek. "Waste Reduction by Lean Construction - Office Building Case Study." IOP Conference Series: Materials Science and Engineering 603 (2019): 042061. https://doi.org/10.1088/1757-899x/603/4/042061.

O'Connor, James T., Neftali Torres, and Jeyoung Woo. 2016. "Sustainability Actions during the Construction Phase." *Journal of Construction Engineering and Management* 142 (7): 04016016. https://doi.org/10.1061/(asce)co.1943-7862.0001128.

Osmani, M., J. Glass, and A.d.f. Price. "Architects' Perspectives on Construction Waste Reduction by Design." Waste Management 28, no. 7 (2008): 1147–58. https://doi.org/10.1016/j.wasman.2007.05.011.

Ogunbiyi, Oyedolapo, Jack Steven Goulding, and Adebayo Oladapo. 2014. "An Empirical Study of the Impact of Lean Construction Techniques on Sustainable Construction in the UK." *Construction Innovation* 14 (1): 88–107. https://doi.org/10.1108/ci-08-2012-0045.

Pampanelli, Andrea Brasco, Pauline Found, and Andrea Moura Bernardes. "A Lean & Green Model for a Production Cell." Journal of Cleaner Production 85 (2014): 19–30. https://doi.org/10.1016/j.jclepro.2013.06.014.

"Policy Framework Procedure," June 12, 2019. https://www.gs.unsw.edu.au/policy/documents/policyframeworkprocedure.pdf.

ramsthaler@un.org. 2014. "Sustainability | Academic Impact." Un.Org. April 2014. https://academicimpact.un.org/content/sustainability.

Saieg, Pedro, Elisa Dominguez Sotelino, Daniel Nascimento, and Rodrigo Goyannes Gusmão Caiado. 2018. "Interactions of Building Information Modeling, Lean and Sustainability on the Architectural, Engineering and Construction Industry: A Systematic Review." *Journal of Cleaner Production* 174 (February): 788–806. https://doi.org/10.1016/j.jclepro.2017.11.030.

Sattary, Sattar. 2004. "Assessment of Sustainable Construction Practices."

Sfakianaki, Eleni. 2015. "Resource-Efficient Construction: Rethinking Construction towards Sustainability." Edited by Dr Catalin Raitu and Dr Beverlee B. An. *World Journal of Science, Technology and Sustainable Development* 12 (3): 233–42. https://doi.org/10.1108/wjstsd-03-2015-0016.

Siegel, Rebecca, Jiju Antony, Jose Arturo Garza-Reyes, Anass Cherrafi, and Bart Lameijer. 2019. "Integrated Green Lean Approach and Sustainability for SMEs: From

Literature Review to a Conceptual Framework." *Journal of Cleaner Production* 240 (December): 118205. https://doi.org/10.1016/j.jclepro.2019.118205.

Tasdemir, Cagatay, and Rado Gazo. 2018. "A Systematic Literature Review for Better Understanding of Lean Driven Sustainability." *Sustainability* 10 (7): 2544. https://doi.org/10.3390/su10072544.

Terry, Jon. "What Is Continuous Improvement?: Planview LeanKit." Planview. Planview, June 18, 2020. https://www.planview.com/resources/guide/lean-principles-101/what-is-continuous-improvement/.

Tezel, Algan, Lauri Koskela, and Zeeshan Aziz. 2018. "Current Condition and Future Directions for Lean Construction in Highways Projects: A Small and Medium-Sized Enterprises (SMEs) gun/doi.org/10.1016/j.ijproman.2017.10.004.

Thomas, Steve A. 2016. *The Nature of Sustainability : Seeking the Physics and Patterns That Underlie Sustainability*. Grand Rapids, Michigan: Chapbook Press.

University of Mary Washington. 2015. "Economic Sustainability." Office of Sustainability. August 11, 2015. https://sustainability.umw.edu/areas-of-sustainability/economic-sustainability.

US EPA,OSWER,ORCR. 2018. "Sustainable Management of Construction and Demolition Materials | US EPA." US EPA. August 22, 2018. https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials.

Waite, Matthew. n.d. "Lean and Sustainability in Construction Survey."

Wassmer, Ulrich, Diego C. Cueto, and Lorne N. Switzer. 2014. "The Effect of Corporate Environmental Initiatives on Firm Value: Evidence from Fortune 500 Firms." *Management* 17 (1): 1. https://doi.org/10.3917/mana.171.0001.

"What Is Plan-Do-Check-Act (PDCA) Cycle?: Kanbanize." Kanban Software for Agile Project Management. Accessed November 30, 2020. https://kanbanize.com/lean-management/improvement/what-is-pdca-cycle.

Womack, J P, and D T Jones. 1997. "Lean Thinking—Banish Waste and Create Wealth in Your Corporation." *Journal of the Operational Research Society* 48 (11): 1148–1148. https://doi.org/10.1038/sj.jors.2600967.

Yin, Samuel Yen-Liang, H. Ping Tserng, Shih Ning Toong, and Thanh Long Ngo. 2014. "AN IMPROVED APPROACH TO THE SUBCONTRACTING PROCUREMENT PROCESS IN A LEAN CONSTRUCTION SETTING." *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT* 20 (3): 389–403. https://doi.org/10.3846/13923730.2013.801900.

IX
BIBLIOGRAPHY

Yu, Miao, Fangwei Zhu, Xiaotian Yang, Linzhuo Wang, and Xiuxia Sun. 2018. “Integrating Sustainability into Construction Engineering Projects: Perspective of Sustainable Project Planning.” *Sustainability* 10 (3): 784. https://doi.org/10.3390/su10030784.

Zaidi, Arjumand, Masroor Ahmed, and Azhar Uddin. 2019. “Environmental Protection with Economic Gain: A Win-Win Situation.” *Www.Preprints.Org*, January. https://doi.org/10.20944/preprints201901.0235.v1.

Zhabrinna, Richard J. Davies, M. Mirza Abdillah Pratama, and Muhammad Yusuf. 2018. “BIM Adoption towards the Sustainability of Construction Industry in Indonesia.” Edited by P. Hajek, A.L. Han, S. Kristiawan, W.T. Chan, M.b. Ismail, B.S. Gan, R. Sriravindrarajah, and B.A. Hidayat. *MATEC Web of Conferences* 195: 06003. https://doi.org/10.1051/matecconf/201819506003.

ZHANG, Lianying, Xi CHEN, and Yongqing SUO. 2017. “Interrelationships among Critical Factors of Work Flow Reliability in Lean Construction.” *JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT* 23 (5): 621–32. https://doi.org/10.3846/13923730.2016.1217921.