Assessing the effects of Lean Construction on Environmental Sustainability using System Dynamics (SD) Approach

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This thesis is dedicated to my beloved parents and my respected teachers!

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ABSTRACT

The increasing global consternation on the environment has created an auxiliary challenge for the construction industry. Most of the activities in construction sector results in huge number of wastes and emissions which are negatively affecting the environment. On the other hand, the environmental sustainability requires the efficient resource use by minimizing waste, reducing emissions and pollution, while encouraging the energy efficiency. In parallel, the lean construction which relies on the principle of eliminating waste is found to be a potential solution to address these issues. The aim of this research is to assess the effects of lean construction on environmental sustainability by classifying the links between them using a system dynamics approach. The study deciphers the impact of lean construction on some environmental parameters such as material usage, carbon emissions, pollution, energy consumption etc. This research provides perceptions into useful and complex causal relationships between lean construction and the environment. The system thinking approach is used to decode these relationships. A system dynamics model is suggested using the system dynamics modelling technique for the consolidation of lean construction and environmental sustainability. The research includes identification of effects of lean construction on environmental sustainability from literature incorporating industry opinion through preliminary survey. The detailed questionnaire survey was used to determine causality among variables that resulted into development of causal loop diagram (CLD). The CLD was used to develop the system dynamics model.

The knowledge incorporated in this paper will inspire the implementation of lean construction, obtaining broader advantages from the perspective of environmental sustainability.

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List of Abbreviations

SD	System Dynamics
LC	Lean Construction
CLD	Causal Loop Diagram
SC	Sustainable Construction
VSM	Value Stream Mapping
JIT	Just in Time
LPS	Last Planner System

Chapter 1

Introduction

1.1 Background of the study

The infrastructure and building segments of the construction industry are frequent consumers of global resources, energy, and materials (Huovila and Koskela, 1998). Furthermore, the sector's operations generate a substantial amount of waste in the form of materials and contaminants, as well as a large amount of greenhouse gas (GHG) emissions (Horvath, 2004). Such environmental consequences are concerning since, according to the 'Stern Review,' the entire costs and climate change risks linked with environmental issues are comparable to losing 5% of world GDP annually (Stern, 2006). The concept of lean construction has the potential to tackle these issues, which emerged in the 1990s as a reaction to the industry's traditional approach (Francis and Thomas, 2019). Lean construction is derived from Toyota Production System inspired production management principles (Ballard and Howell, 2003). Lean Construction is a concept centered on eliminating waste, reducing cycle time, optimizing workflow, and increasing process efficiency by eliminating everything that does not contribute value to the process. However, the majority of these studies have solely evaluated it based on the economic gains received, as this has been the primary motive for implementing lean construction. If the sole goal of lean philosophy is to obtain economic benefits in the form of lower costs and higher profits, it may have unforeseen environmental consequences (Song and Liang, 2011). The recent emphasis on environmental protection might provide a backdrop for assessing the impact of lean construction on environmental parameters such as pollution, waste, natural resource use, and emissions (Francis and Thomas, 2019). Environmental sustainability in construction is primarily concerned with minimizing material waste, water conservation, pollution reduction, dust management, the use of environmentally friendly materials and procedures, and encouraging recycling, all of which help to reduce the impact on biodiversity (Cib and Unep-Ietc, 2002). The emphasis on wasteminimization and resource efficiency in lean philosophy represents the fundamental principle of environmental sustainability. Both construction and the environment are complex systems with multiple stakeholders and several components.

System Dynamics is a useful approach for examining the dynamic relationships between the system's stakeholders and components (Yuan and Allen, 2011). Using a system dynamics approach, the study will explore the effects of lean construction on environmental sustainability. The System Dynamics method is a way of thinking about how a system evolves through time. System behavior describes the parts and factors that make up a system that varies over time. The WORLD 2 and WORLD 3 were two models developed at the Massachusetts Institute of Technology (MIT) in the early 1970s (Saavedra M., Cristiano and Francisco, 2018). System Dynamics is a simulation method for addressing real-world problems and illustrating correlations between variables in complicated real-world systems.

1.2 Problem statement

Lean construction is considered as a way out to address construction related problems by eliminating waste and increasing reliability, and a recent study shows that it has significant potential in addressing sustainability problems as well (Francis and Thomas, 2019). However, most studies in this domain are greatly diverse in their approaches and concentrate more on productivity and quality thus making a disintegrated understanding, and do not collectively analyze the multiple feedbacks and interlinks impacting environmental sustainability. In order to cover this gap, the study will address the complexities in assessing the effects of lean construction on environmental sustainability in the construction sector.

1.3 Level of research already carried out on the proposed topic

The lean strategies implemented in the projects that resulted in green outcomes were highly acknowledged (Riley *et al.*, 2005). Other studies, such as those done by Nahmens (2009) and Zimmer (2005), revealed evidence that by the adoption of the lean concepts waste can be minimized. As the traditional project management strategies started failing, lean construction philosophy came into existence, resulting in major development in project management and deliverables (Koskela *et al.*, 2002). Lean construction is an expanding idea that involves applying lean thinking to the construction industry. In the UK construction industry, lean construction is majorly implemented for increasing quality and efficiency (Green, 1999). Multiple kinds of research have been conducted to determine the benefits and drawbacks of lean construction on environmental characteristics in order to create a link between the two areas. A major portion of the current research attempts to establish a link between lean construction and overall sustainability, which includes economic, environmental, and social factors. Existing research demonstrates the impact of lean construction on long-term economic viability through better process efficiency, reduced variability, and increased output. Social sustainability, on the other hand, is demonstrated byfewer accidents and a safer environment, both of which are achieved through lean construction. Lean construction can also play a vital role in benefitting the environment by reducing emissions and reducing resource waste in the construction process.

1.4 Justification for selection of the topic

The construction industry throughout the world substantially requires to embrace the principles of lean in its activities and policies (Brandon and Lombardi, 2005). Nevertheless, many activities in construction have cynical impacts on the environment through the generation of construction and demolition wastes. The construction industries of developing countries are more concerned about productivity and quality with very less or no concern about environmental impacts. There is a need to emphasize environmental sustainability because this is a very vital step toward sustainable development and the future of construction is dependent on the environment. We should learn from the developed countries like the UK where multiple types of research have been conducted on Lean Construction and this philosophy is behind many distinguished projects including "Heathrow's Airport Terminal 5". Last Planner System (LPS) was applied in airport expansion which is the foundational approach for Lean Construction. They have found it very suitable from the aspect of environmental sustainability and during the construction of Athletes Village for the 2012 Olympics held in London, the project team used a lean Construction training program due to which waste generation was decreased by 13% in six-month and saved an amount £94000 in the disposal costs of waste.

Nowadays especially in our country, there is an emerging concern for the environment related problems and we are moving towards the goal of a sustainable environment. So, this study will help to the understand the effects of lean construction on the environment and further it will also contribute in making construction-related policies supplementing the environmental sustainability.

1.5 Objectives

The objectives of this thesis research are:

- To identify the effects on environmental sustainability by the adoption of lean construction philosophy.
- To evaluate the importance, interconnectivity and functionality amongst the identifiedeffects.
- To develop a System Dynamics model to address the complexities in assessing the effects of lean construction practices on the environment in the construction sector.

1.6 Relevance to National Needs

In developing countries, the construction sector is already lagging in protecting the environment and reducing waste. There is very little recognition of factors that are affecting the environment negatively. The construction sector is considered the largest source of employment generation in the World and there is a lack of sustainable practices and understanding of environmental sustainability. Traditional construction practices are followed with the productivity in mind and with no concerns for the environment, there is a need for considering and adopting sustainable practices with the aim of considering environment as a stakeholder. There is already a scarcity of materials and resources and in the future things are going to be worst. Therefore, there is a need for aconstruction revolution in our country and there is a big room for research in lean construction and environmental sustainability.

Chapter 2

Literature Review

2.1 Construction industry

Construction is one of the biggest sources of employment generation in a country and plays a major part in its economy (Isa, Jimoh and Achuenu, 2013). There is a French saying:

"When the construction industry prospers everything prospers."

The major concern of the construction sector is the enhancement of the economic, social and environmental sustainability indicators (Ullah, Noor and Tariq, 2018). The industry creates civil engineering products by utilizing energy, materials, and other resources. The result of all these activities is huge volumes of waste during and at the end of the facility's life.

2.2 Characteristics of the Construction sector

The infrastructure and building categories of the construction industry are major consumers of global resources, energy, and materials (Huovila and Koskela, 1998). Furthermore, the sector's activities generate substantial amounts of waste in the form of materials and contaminants, as well as a significant amount of greenhouse gas (GHG) emissions (Horvath, 2004). According to the 'Stern Review', the entire costs and climate change risks connected with environmental concerns are comparable to losing 5% of global GDP annually (Stern, 2006).

2.3 Lean Construction (LC) –An introduction

Lean Construction philosophy has derived from the Toyota Production System (TPS) which mainly concentrates on enhancing the process efficiency by eradicating anything that is not adding value to the customer (Womack and Jones, 1996). Lean Construction considers a construction project as interim production system and aims to deliver the project with maximized value and minimized waste (Howell and Koskela, 2000). The collapse of the old project management strategies resulted in the birth of Lean construction, which transformed the dynamics of management and project deliverables (Koskela and Howell, 2002). However, lean philosophy received appreciation in the construction domain because it challenges the conventional approaches of the industry by introducing the idea of 'value' and defines waste in a much broader spectrum in construction. Therefore, the concept of lean construction aroused that was a term introduced by the international group of lean construction (IGLC) in a first meeting in 1993.

2.4 Lean philosophy in the construction sector

The principles of lean are devised to enhance the construction process by reducing waste and eliminating activities that are not generating value (Howell and Koskela, 2000). Lean construction is considered to be a robust manufacturing philosophy that has ample potential to revolutionize the construction sector. As the construction industry faced the problem of lowering the environmental effects of its material and energy use, the demand for more innovation in construction has amplified (Bates, Sturges and Hutchinson, 1999). Lean construction can be simply defined as the implementation of the lean approach to the design and construction process, resulting in improved delivery of a project that is up to the client's demands along with an increase in functionality and profitability (Akanbi, Oyedolapo and Steven, 2019). It majorly concentrates to enhance the overall value rather than only minimizing the expense.

The five essential lean concepts include:

- the recognition of the worth from the customer's perception.
- mapping the value stream.
- creating flow within the work.
- attaining customer pull at the appropriate point in time.
- aiming for perfection.
- continuous improvement.

2.5 Lean construction and environmental sustainability

The Lean Construction approach is an unspoken method that has been discovered to have the ability to lessen environmental consequences (De Carvalho, Granja and Da Silva, 2017). Enhancement of environmental sustainability in construction mainly depends upon minimizing material waste, water conservation, pollution reduction, dust control, the use of sustainably sourced materials and methods like encouraging recycling, all of which help to reduce the impact on biodiversity (Cib and Unep-Ietc, 2002). Multiple researchers have found a strong connection between lean construction and environmental sustainability since it has been found to reduce diminution of resources and pollution by minimizing waste and offering more value to customers in the term of reduced environmental impacts (Solaimani and Sedighi, 2020). The significance of minimizing waste and resource efficiency in lean philosophy reflects the underlying principle of environmental sustainability. In this context, Vieira and Cachadinha (2011) proposed that, despite the fact that environmental benefits from lean construction practices are an unanticipated result, the industry should implement them with reassigned additional social and environmental goals to help achieve sustainable development.

2.6 Waste in the lean language and its consequences on the environment

The idea of waste elimination is the key variable between lean construction and the environment (Nahmens, 2009). The lean construction philosophy defines waste in a much broader spectrum. Lean thinking splits a process into value-adding and nonvalue-adding activities (waste). The former category covers actions that process materials and information in order to provide the value that the client desires. The latter includes actions that use resources while not adding value to the end product. However, defining value in the building process is difficult due to the numerous support activities that lack in providing value but are required.

2.6.1 Types of waste in the lean context and their environmental impacts

In the context of construction, the seven key wastes identified by literature in relation to lean philosophy, namely transportation, waiting, overproduction, defects, inventory, motion, and extra-processing (Womack and Jones, 1996), are listed and briefly discussed in Table I.

Table I: Waste types in Lean Context

Category	Definition	Examples	Impacts on environment sustainability
Defects	Failure to achieve the scope/expectations/compliance results in waste.	Flaws in design demand rework.	Waste generation, emissions, wastage of material and energy.
Overproduction	Resources are being wasted by producing more than necessary or demanded.	Too many frames are being prepared for the pouring of concrete.	Wastage of material, energy and resources.
Waiting	Stopping an action to allow another (dependent) activity to finish first generates waste.	A loader stands by, waiting for a truck to return to the loading area.	Increase in energy consumption, emissions and probability of wastage of material.
Transportation	Unnecessary movement of tools, materials, and equipment causes waste.	Because of the poor quality ofthe access roads, the equipment is moving slowly.	Emissions and increase in energy consumption.
Inventory	Waste of materials at storage.	Purchasing resources in excess of what is required and then wasting them.	Wastage of material in the form of leakages and spills, generation of hidden waste.
Motion	Unnecessary mobility of people on the construction site.	Site Engineer frequently driving to site for signing permits.	Increase in energy consumption and emissions.
Over-processing	Excessive resource waste as a result of going beyond the scope of the project.	Spending too much effort on aesthetics (above what is required by the scope) may cause delays.	Increase in material, resource and energy use.

2.7 Lean construction tools and their impact on environmental parameters

Despite the fact that the Lean Construction philosophy originated from Toyota's production system philosophy, it differs in terms of conception and implementation. The lean design has evolved and embraced two completely distinct application models (Babalola, Ibem and Ezema, 2019). These techniques of putting lean ideas into practice are referred to as lean tools. One technique tries to adapt lean tools straight from the production environment to the build (5S, Value Stream Mapping (VSM), Just-in-Time (JIT)), while the other is based on the original philosophy and strives to create a new set of tools that are unique to construction (e.g., Last Planner System (LPS)). Here are some techniques that were developed to help interpret the lean philosophy's implications on environmental sustainability. It's worth noting that the lean tools discussed in this section are ones that arose directly from the concepts of lean construction; they don't include other generic tools used by lean practitioners to assist lean thinking.

2.7.1 5 S

The 5S technique, which stands for "sort, standardize, shine, straighten and sustain" is a lean tool that is used as a very first step toward adopting lean construction by many firms (Salem *et al.*, 2014). This technique consists of labelling and arranging material(inventory management), due to which hazardous spills and leaks can be rapidly detected and simultaneously aids in the reduction of air pollution (Vieira and Cachadinha, 2011). The 5S technique has been applauded in the Leadership in Energy and Environmental Design rating system, which is used as a grading meter for green buildings (Bae and Kim, 2008). The credit was given due to the fact that 5S furnished an accident-free, healthy and clean work environment for the workers. Similarly, the 5S was implemented in paving project work zones to minimize waste and pollution, hence enhancing environmental sustainability (Salem *et al.*, 2014). Therefore, 5S is found to be centrally associated with environmental sustainability principles.

2.7.2 Just in Time

This is the most frequently adopted lean tool in the construction industry is the Just-in-Time (JIT), which is strongly tied to the pull principle (Ogunbiyi, Oladapo and Goulding, 2014). It concentrates on procurement of the correct resources at right time and keeping the inventory at optimal levels (Cherrafi *et al.*, 2016). When it comes to environmental considerations, the application of JIT in the construction industry is debatable. If JIT is used more frequently than it might result in an increment of emissions released during transportation (Rothenberg, Pil and maxwell, 2001). Due to this problem, multiple companies in the United States and Japan have agreed to alter their JIT principles to decrease traffic congestion which causes pollution and aid environmental sustainability (Cusumano, 1994). However, JIT has been acknowledged in building projects as a way to avoid material damage and degradation caused by excessive inventory, as well as any energy usage or emissions that may occur otherwise (Riley *et al.*, 2005). The local availability of supplies and minimum transport distances, make JIT justifiable from the perspective of environmental sustainability in construction. As a result, it's critical to assess the impact of JIT implementation on building sites based on the feasibility of JIT delivery and the environmental consequences (Vieira and Cachadinha, 2011).

2.7.3 Prefabrication

In lean supply philosophy, prefabrication is considered the most essential element and it entails fabricating various building elements in a controlled off-site environment before transporting them to construction projects to be assembled. This supplements a better supply chain of materials, recycling, and waste management, and thus supports environmental sustainability. Prefabrication can assist in minimizing material use, as well as energy and water demands, resulting in environmental advantages (Riley *et al.*, 2005). To further understand the influence of the lean concept on emissions, we can consider research conducted by Peng and Pheng (2011) in precast concrete manufacturers. According to the study, lean implementation at the precast yard resulted in an 8.3 percent reduction in carbon emissions, demonstrating that environmental performance and production efficiency can be improved. In research by Bhattacharjee (2016), two distinct elements are compared, one of which employs prefabricated components and the other which uses conventional construction. The pre-cast component outperforms the cast section in terms of cost, quality, and time, reduces rework, and consequently benefits the environment. Prefabrication, like JIT, can result in increased energy consumption and pollution if additional transportation is necessary to supply the prefabricated pieces (Kim and Bae, 2010). The location of the prefabricated shipyards is a controlling factor in assessing the environmental effect in this case.

2.7.4 Value Stream Mapping (VSM)

Another known lean tool is Value Stream Mapping (VSM), which is used in mapping process flows by combining time and information streams and visualizing the whole process. The identification of multiple hidden wastes in the value stream and trying to minimize them is the primary function of VSM (Rother and Shook, 2003). It is a user-friendly tool that is very adaptable and delivers both quantitative and qualitative process analyses (Seth, Seth and Dhariwal, 2017). First, it captures the process as it is in the existing state map, and then it carefully examines this record to detect any lean waste that may exist. Furthermore, evaluate it to discover opportunities for improvement and make recommendations. After that, a future state map is created, which portrays the ideal but realistic situation of the process after it has been optimized (Sergio, Mauricio and Vicente, 2014). After assessing the current condition maps, this VSM was combined with numerous environmental indicators to identify various material waste (steel and concrete) and energy waste (fuel). This simplified depiction, in addition to the normal time indications (delivery time, changeover time, cycle time), made it possible to quickly detect congestions in the process of preparing future state maps, as well as advocate waste reduction and suitable allocation. Hence, it is critical to consider that the VSM is a possible visual tool for identifying various lean wastes and that it may also be used to identify environmental consequences. VSM has become a robust lean tool that might assist achieve environmental sustainability due to its flexibility and simplicity, and there are various modified variants of VSM in both manufacturing and construction.

2.7.5 Last Planner System (LPS)

It is an excellent lean tool developed by the construction industry and based on the original lean manufacturing concept. LPS is a collaborative planning scheme that tries to guarantee that all construction process requirements and limits are taken into consideration in the preliminary phases of planning so that activities can be completed uninterruptedly and within the time (Ballard and Howell, 2003). Although LPS is not a direct environmental instrument, it does have an indirect influence on projects that affect long-term sustainability or green aspects (Valente, Mourão and De Neto, 2013). LPS allows for the handling of new limitations as well as the flexibility needed to incorporate changes. The most significant relationship between lean and green Construction, is cooperation along with accountability and it can be effectively enabled through LPS (Maris and Parrish, 2016). It also aids in the formulation of better sustainability related strategic decisions. LPS is a key component in enhancing process speed and decreasing emissions in paving projects (Salem *et al.*, 2014). Paving project work zones produce very insecure traffic, which also pollutes the environment. The study reveals that adhering to the LPS principles reduces traffic instability by better coordinating operations. In another research, the difference in CO2 emissions between two similar projects (one of which was executed using LPS) was compared (Ghosh *et al.*, 2014). By the adopting LPS, the project was able to detect restrictions ahead of time, reducing the amount of material and labor waste that may have come from rework. In a single component process, it resulted in a 6% decrease in material waste and emissions of roughly 7.5MT CO_2 equivalent, which is a substantial improvement. LPS is used for the renovation and delivery of a net zero energy workplace in Arizona in separate research by Parrish. LPS aided in improving collaborative planning and ensuring that the entire team's aim is attainable. In the net-zero energy structure, it would create as much energy as it consumed (Ladhad and Parrish, 2013). These findings suggest that, while LPS does not have any explicit environmentally focused objectives but it does have an indirect impact on environmental factors.

2.6 System dynamics approach

A system dynamics (SD) simulation helps to understand the complex system's behavior over time by considering the various dynamic factors that influence the system under consideration (Sterman, 2000). Jay Wright Forrester presented System Dynamics (SD) ideas during the 1950s. The main objective of the SD methodology was to support industrial processes where variables are connected to a system which is dynamic in nature. System dynamics is mainly designed for complex, huge socio-economic systems (Forrester, 1997). System dynamics (SD) modelling is an instrumental philosophy for the detailed evaluation of a complex system (Xu and Coors, 2012). System dynamics is a modelling process that involves iterations. SD model is constructed by the utilization stocks and flows, feedback loops, table functions and time delays (Coyle, 1997). A causal loop diagram is created to find the relationship between variables, reinforcing and balancing feedback loops in the exhaustive system (Nguyen and Bosch, 2013). Each pair of variables in SD models consist of cause and effect representing that the variables can travel in the same or opposite direction. The Polarities between links only predict the consequences of change, they don’t show the behavior of variables (Sterman, 2000).

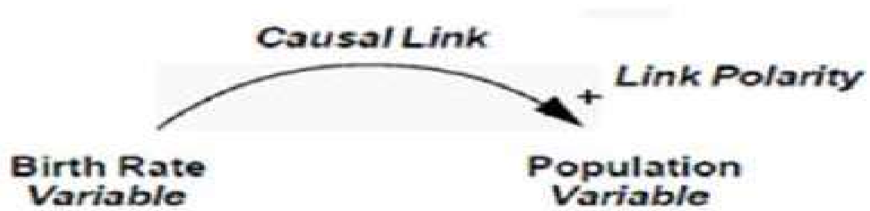

Figure 1: Causal Loop and Polarity

Polarity is found by tracing the effects of the variable as it propagated around the loop. A positive loop is shown by **"R"** depicts the actions that produce a result and arise further while a negative loop is shown by **"B"** which directs state of system in opposite direction (Coyle ,2000).

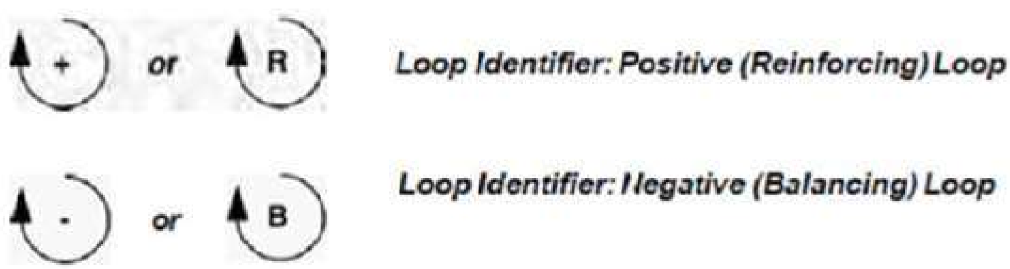

Figure 2: Positive and Negative loops

The robustness of the system dynamics approach is that it traces and elucidates a given system over some time, amalgamating multiple theories, techniques and philosophies that support providing functional framing, and grasping the behavior shown by the system (Forrester, 1997). The System dynamics models are the composition of three categories of variables: stock, flow and auxiliary. While the flows are of two categories, material and information both of which could interact and respond to others. The combination of variables with stock and flows are necessary components of the stock-flow diagram in which a crucial role is played by feedback loops for the simulation of the model.

Research Methodology

3.1 Introduction

The study focuses on the effects of lean construction on environmental sustainability using a system dynamics approach. The research is carried out in four main phases. The pictorial representation for the framework of this research is presented in figure 3.

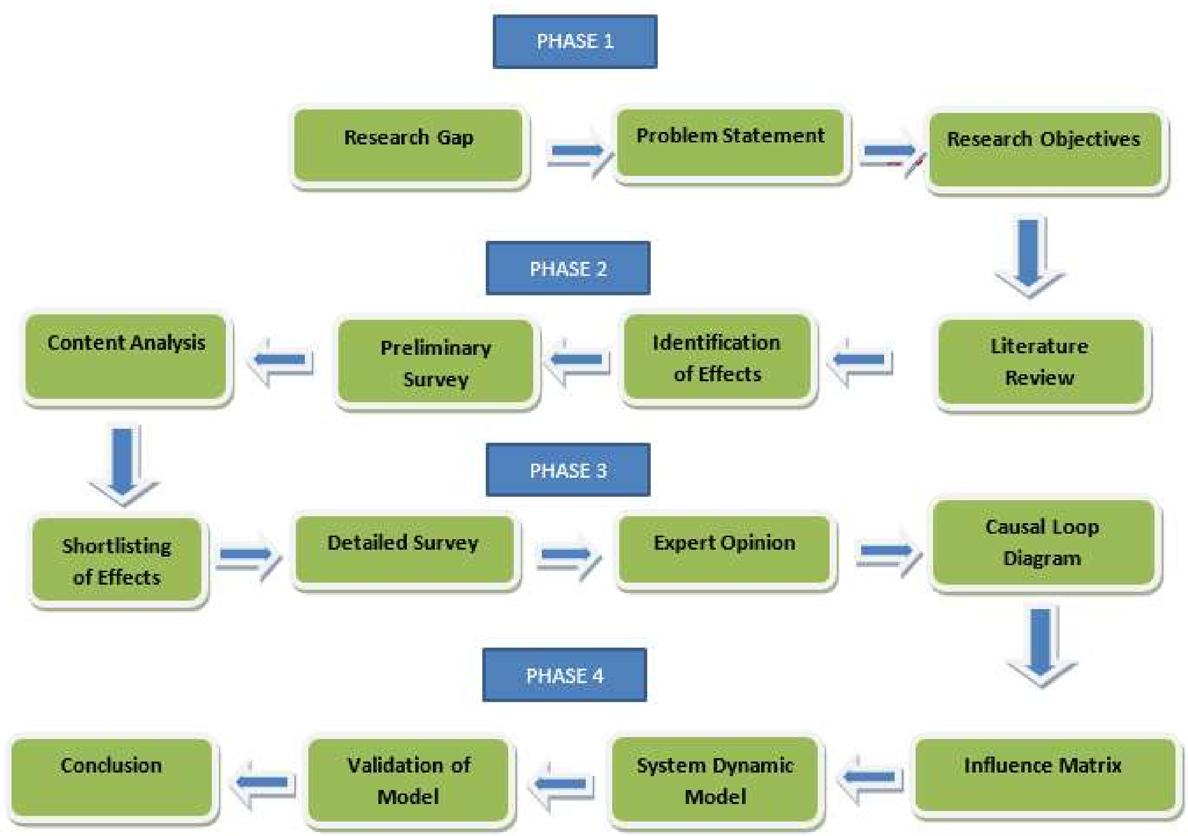

Figure 3: Flow chart of Research Methodolog

3.1.1 Phase 1: Identification of research objectives

This phase comprises basic steps such as finding the research gap and research topic. The exploration of literature was done from research articles, books and conference papers for establishing this gap. After the elaboration of the problem statement, the objectives of the research were recognized. This method helped in answering certain questions such as work already done on this topic? Why is this research carried out? What would be its advantages to the construction industry? What will be its relevance to national needs?

3.1.2 Phase 2: Literature review and preliminary survey

In this phase literature review was done to identify the effects on environmental sustainability by the adoption of the Lean Construction philosophy. A total of 29 research papers were reviewed for identifying the effects on environmental sustainability by the adoption of lean construction philosophy. Data analysis revealed 28 effects on the environment by the adoption of lean construction. Content analysis was conducted to scrutinize the most important effects. This was done using a literature score and field survey. The identified effects from the literature were given rank according to their literature scores. This was done through a content analysis where the impact of each effect (low, medium and high) was assessed through a detailed review of the literature. Each impact was quantified by using numbers (high (5), medium (3) and low (1)) as described in the study. The highest frequency impact was considered for each effect. In order to enhance the quality of work the literature review was validated by preliminary survey. The further step was to convert this literature score into a normalized score which was obtained by the division of individual literature scores of each effect with the summation of the literature score. Similarly, the industry score was normalized based on their overall score. The cumulative scores were calculated by the arrangement of these normalized scores in descending order. This technique is used for removing of least significant factors (Ullah *et al.*, 2017).

3.1.3 Phase 3: Detailed Questionnaire Survey for shortlisting of interrelationships

Data was gathered via a detailed questionnaire and the most critical effects were evaluated, while the remainder were crossed off the list. Expert input was obtained during this phase, for which a questionnaire survey was distributed (to shortlist interrelationships among effects and determine polarity), which aided in the formulation of an influence matrix. The next step was to draw a causal loop diagram in conformance with shortlisted causal relationships to make it collateral and meaningful to the construction sector (Tahir, Khan and Nasir, 2021)..

3.1.4 Phase 4: Development of System Dynamics Model

This is the most crucial stage of the study. Expert opinion was incorporated in this phase to examine the influence effects on the formulation of equations for the system dynamics model. To address complexities in assessing the effects of lean construction on environmental sustainability, a causal loop diagram was created, followed by a System Dynamics model. The most essential element of the research which discussion, findings, and future recommendation of the research following this phase.

RESULTS AND DISCUSSIONS

4.1 Preliminary Questionnaire Survey

A preliminary questionnaire-based survey was conducted to obtain response from industry for which a questionnaire form was created in **Google®**. Respondents were requested to suggest the importance of each factor on a scale of 1 (minimum) to 5 (maximum).

4.1.1 Ranking of effects based upon Field Score + Literature Score

The industry normalized score and literature normalized score were combined to get the final ranking of effects. The ratio used in this respect is 60/40 (60% score dedicated to industry and 40% to literature).

Table II: Ranking based on the total cumulative normalized score by using a 60/40 ratio

Sr. No	Effects on environmental sustainability by adoption of LC	Total Score 60/40	Cumulative Normalized Score	Reference
1.	Waste Minimization	0.0835	0.0835	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017) ;(Wai M., Leong and Vichare, 2017) ;(Dixit *et al.*, 2017) ;(Babalola, Ibem and Ezema, 2019) ;(Mohd Arif, Nor Azmi and Aini, 2019) ;(Carvajal-Arango *et al.*, 2019) ;(Dieste *et al.*, 2019) ;(Babalola, Ibem and Ezema, 2019) ;(Li, Fang and Wu, 2020) ;(Francis and Thomas, 2020) ;(Solaimani and Sedighi, 2020)
2.	Reduction in Energy Consumption	0.0631	0.1466	(Dave, Koskela and Kiviniemi, 2013) ;(Ogunbiyi, Oladapo and Goulding, 2014) ;(Belayutham, González and Yiu, 2016) ;(Bajjou *et al.*, 2017) ;(Martínez León and Calvo-Amodio, 2017) ;(Dixit *et al.*, 2017)

				;(Babalola, Ibem and Ezema, 2019) ; (Mohd Arif, Nor Azmi and Aini, 2019) ;(Francis and Thomas, 2019) (Carvajal-Arango *et al.*, 2019); (Tafazzoli, Mousavi and Kermanshachi, 2020) ;(Solaimani and Sedighi, 2020)
3.	Pollution	0.0585	0.2052	(Marhani *et al.*, 2013) ;(Belayutham, González and Yiu, 2016) ;(Martínez León and Calvo-Amodio, 2017) ;(Bajjou *et al.*, 2017) ;(Martínez León and Calvo-Amodio, 2017) ;(Dixit *et al.*, 2017) ;(Francis and Thomas, 2019) ;(Carvajal-Arango *et al.*, 2019); (Solaimani and Sedighi, 2020) ;(Francis and Thomas, 2020)
4.	Facilitation of green Features	0.0474	0.2527	(Garza-Reyes, 2015) ;(Martínez León and Calvo-Amodio, 2017) ;(Wai M., Leong and Vichare, 2017) ;(Dixit *et al.*, 2017) ;(Babalola, Ibem and Ezema, 2019) ;(Solaimani and Sedighi, 2020) ;(Mohd Arif, Nor Azmi and Aini, 2019)
5.	Reduction in Carbon Footprint	0.0429	0.2956	(Dave, Koskela and Kiviniemi, 2013) ;(Salem *et al.*, 2014) ;(Belayutham, González and Yiu, 2016) ;(Martínez León and Calvo-Amodio, 2017) ;(Martínez León and Calvo-Amodio, 2017) ;(Dixit *et al.*, 2017) ;(Wai M., Leong and Vichare, 2017) ;(Dieste *et al.*, 2019) ;(Francis and Thomas, 2020) ;(Li, Fang and Wu, 2020) ;(Heravi, Rostami and Kebria, 2020)
6.	Sustainably sourced material	0.0412	0.3369	(Dave, Koskela and Kiviniemi, 2013) ;(Martínez León and Calvo-Amodio, 2017) ;(Bajjou *et al.*, 2017) ;(Dixit *et al.*, 2017) ;(Martínez León and Calvo-Amodio, 2017) ;(Babalola, Ibem and Ezema, 2019) ;(Solaimani and Sedighi, 2020) ; (Francis and Thomas, 2020) ;
7.	Less Hazardous Waste	0.0412	0.3781	(Belayutham, González and Yiu, 2016) ;(Bajjou *et al.*, 2017) ;(Wai M., Leong and Vichare, 2017) ;(Dieste *et al.*, 2019) (Babalola, Ibem and Ezema, 2019) ; (Carvajal-

				Arango *et al.*, 2019) ;(Francis and Thomas, 2020)
8.	Reduced Greenhouse Gases Emissions	0.0381	0.4162	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017) ;(Dixit *et al.*, 2017) ;(Mohamad Sedighi, 2019) ;(Francis and Thomas, 2020) ;(Carvajal-Arango *et al.*, 2019) ;(Li, Fang and Wu, 2020)
9.	Elimination of Hidden waste	0.0381	0.4543	(Salem *et al.*, 2014) ;(Bajjou *et al.*, 2017) ;(Dieste *et al.*, 2019) ;(Li, Fang and Wu, 2020) ;(Francis and Thomas, 2020) ;(Solaimani and Sedighi, 2020)
10.	Improvement in Environmental Quality	0.0381	0.4924	(Dave, Koskela and Kiviniemi, 2013) ;(Ogunbiyi, Oladapo and Goulding, 2014) ;(Bajjou *et al.*, 2017) ;(Mohd Arif, Nor Azmi and Aini, 2019) ;(Dieste *et al.*, 2019) ;(Li, Fang and Wu, 2020), (Francis and Thomas, 2020)
11.	Fuel Consumption	0.0373	0.5297	(Dave, Koskela and Kiviniemi, 2013) ;(Salem *et al.*, 2014) ;(Bajjou *et al.*, 2017) (Wai M., Leong and Vichare, 2017) ;(Martínez León and Calvo-Amodio, 2017) ;(Martínez León and Calvo-Amodio, 2017) ;(Francis and Thomas, 2020)
12.	Reduction in Water Consumption	0.0362	0.5660	(Dave, Koskela and Kiviniemi, 2013) ;(Ogunbiyi, Oladapo and Goulding, 2014) ;(Bajjou *et al.*, 2017) ;(Dieste *et al.*, 2019) ;(Carvajal-Arango *et al.*, 2019) ;(Francis and Thomas, 2020)
13.	Minimized Wastage of Material in stock	0.0335	0.5995	(Ogunbiyi, Oladapo and Goulding, 2014) ;(Bajjou *et al.*, 2017) ;(Babalola, Ibem and Ezema, 2019) ;(Francis and Thomas, 2020)
14.	Eco Efficiency	0.0335	0.6331	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017) ;(Dieste *et al.*, 2019)
15.	Elimination of Hidden Waste Generation Activities	0.0316	0.6648	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017) ;(Wai M., Leong and Vichare, 2017) ;(Dixit *et al.*, 2017) ;(Babalola, Ibem and Ezema, 2019) ;(Francis and Thomas, 2020)
16.	Improved	0.0306	0.6954	(Ogunbiyi, Oladapo and Goulding, 2014) ;(Bajjou *et al.*, 2017) ;(Bajjou *et al.*, 2017)

	Waste Handling			;(Francis and Thomas, 2020) ;(Solaimani and Sedighi, 2020)
17.	Reduction in Excess Inventory	0.0304	0.7258	(Dave, Koskela and Kiviniemi, 2013) ;(Akanbi, Oyedolapo and Steven, 2019) ;(Francis and Thomas, 2020)
18.	Elimination of Overproduction	0.0287	0.7546	(Francis and Thomas, 2020);(Carvajal-Arango *et al.*, 2019)
19.	Early Identification of Spills & Leakages	0.0279	0.7825	(Dieste *et al.*, 2019); (Ansah and Sorooshian, 2017) ;(Francis and Thomas, 2019)
20.	Landfill Minimization	0.0279	0.8104	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017) ;(Dieste *et al.*, 2019)
21.	Reduced Noise Pollution	0.0260	0.8365	(Salem *et al.*, 2014) ;(Bajjou *et al.*, 2017) ; (Francis and Thomas, 2020)
22.	Recycling Maximization	0.0256	0.8621	(Dave, Koskela and Kiviniemi, 2013) ;(Carvajal-Arango *et al.*, 2019) ;(Solaimani and Sedighi, 2020) ;(Albert Thomas, 2019)
23.	Affection of Soil Quality Decreases	0.0260	0.8882	(Bajjou *et al.*, 2017) ; (Dieste *et al.*, 2019) ;(Carvajal-Arango *et al.*, 2019)
24.	Decreased Visual Impact	0.0249	0.9132	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017) ;(Carvajal-Arango *et al.*, 2019)
25.	Increased Usage of Recycled Raw Material	0.0231	0.9363	(Bajjou *et al.*, 2017) ;(Carvajal-Arango *et al.*, 2019); (Francis and Thomas, 2019)
26.	Bio Diversity Protection & Enhancement	0.0212	0.9575	(Dave, Koskela and Kiviniemi, 2013) ;(Bajjou *et al.*, 2017)
27.	Reduction in Contamination of Products	0.0212	0.9787	(Carvajal-Arango *et al.*, 2019) ;(Dieste *et al.*, 2019)
28.	Less Storage of Raw Materials	0.0212	1.0000	(Dieste *et al.*, 2019) **;**(Solaimani and Sedighi, 2020) **;**(Francis and Thomas, 2020)

4.1.2 Shortlisted Effects

The effects on environmental sustainability by the adoption of lean construction were finalized and they were assigned code pertaining to 60% of the cumulative normalized as the cutoff point and thirteen effects came under this criteria having a cumulative normalized score under 60% (Ahmad, Thaheem and Maqsoom, 2018).

Table III: Shortlisted effects having Cumulative normalized scores under 60%.

Code	Effects on environmental sustainability by adoption of LC	Normalized Literature Score	Normalized Industry Score	Total Score 60/40	Cumulative Normalized Total Score	Rank (40/60 Ratio)
F1	Waste Minimization	0.14844	0.04032	0.08357	0.08357	1
F2	Reduction in Energy Consumption	0.10938	0.03226	0.06311	0.14668	2
F3	Pollution	0.08594	0.04032	0.05857	0.20524	3
F4	Facilitation of Green Features	0.07031	0.03226	0.04748	0.25273	4
F5	Reduction in Carbon Footprint	0.04688	0.04032	0.04294	0.29567	5
F6	Sustainably sourced material	0.05469	0.03226	0.04123	0.33690	6
F7	Less Hazardous Waste	0.05469	0.03226	0.04123	0.37813	7
F8	Lowered Greenhouse Gases Emissions	0.04688	0.03226	0.03811	0.41624	8
F9	Elimination of Hidden waste	0.04688	0.03226	0.03811	0.45434	9
F10	Improvement in Environmental Quality	0.04688	0.03226	0.03811	0.49245	10
F11	Fuel consumption	0.03281	0.04032	0.03732	0.52977	11
F12	Reduction in Water Consumption	0.04219	0.03226	0.03623	0.56600	12
F13	Minimized Wastage of Material in stock	0.02344	0.04032	0.03357	0.59957	13

4.2 Detailed Questionnaire Survey

A comprehensive and conclusive questionnaire was prepared using Google® and included 156 causal relationships with polarity. Respondents were asked to rank causal relationships on a Likert scale and polarity (direct or indirect). Because of the extensive nature of the detailed questionnaire, respondents were requested to give their feedback in a grid format (combined level of influence and polarity) to enable their prompt response.

4.2.1 Sample Size

The optimum sample size was evaluated through an equation imparted by (Ephantus *et al.*, 2015).

$$\mathbf{n} = {}^{\mathbf{N}}\!/_{\mathbf{1}+\boldsymbol{N}(\mathbf{e})^{\mathbf{2}}} \qquad \textbf{Eq. 1}$$

$$n = 78/1+78(0.05)^2 = 65$$

Here n = the anticipated sample size, e = probability of error (i.e., the desired precision, 0.05% for 95% confidence level, N= 78, the estimated responses from valuable respondents) required minimum sample size comes out to be 65 (Chan *et al.*, 2017).

4.2.2 Respondents Detail

The data was collected from 80 respondents, out of which 15 were invalid, and 65 actual responses were used for the analysis. In terms of qualification, 30.8% were a bachelor's in civil engineering, whereas 58.5% of the respondents were master's degree holders and leftover 10.8% of the respondents were PHD degree holders. The professional experience of 33.8% of the respondents ranged from 1 to 5 years and 33.8% of the respondents had 6 to 10 years of experience. Similarly, 29.2% of proficient had 11 to 15 years of extensive experience and 3.1% of informants had equal or greater than 20 years of professional experience. Concerning the field work of respondents, the majority of the respondents had exposure to construction management and project management and the rest of the respondents were from quantity survey, building design, architects and consultancy domains.

Table IV: Frequency distribution of responses

Profile	Frequency	Percentage
Total responses = 65		
Field		
Project Management	17	26%
Construction Management	18	27%
Site Execution	13	20%
Architectural	07	10.8%
Building Design Consultancy	06	9.2%
Quantity Surveying	02	3.1%
Consultancy	02	3.1%
Qualification		
Bachelors (B.Eng./B.Sc.)	20	30.8%
Master (M.Sc.)	38	58.5%
Doctorate (PhD/D.Eng.)	7	10.8%
Professional Experience		
0 to 5 years	22	33.8%
6 to 10 years	22	33.8%
11 to 15 years	19	29.2%
16 to 20 years	2	3.1%

4.2.3 Organization Type

With the connection to organization type, 27.7% of the respondents were from contractor organizations while 30.8% were from the client domain. Likewise, 20% of the respondents were from the consultant side while 6.2% were from specialty or petty contractors. The remaining 13.8% were from the academic domain and 1.5% were from the subcontractor's domain.

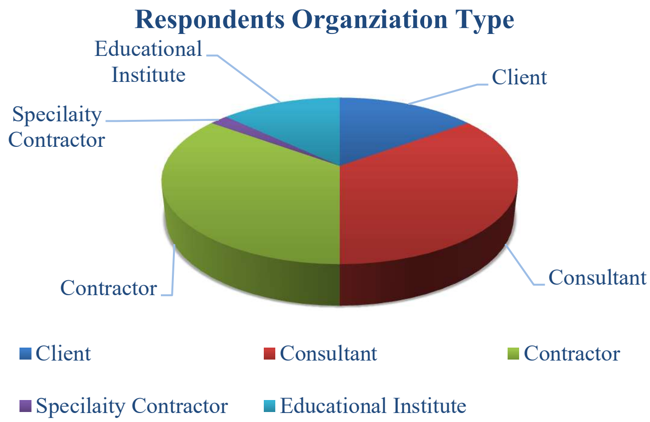

Figure 4: Organization type

4.2.4 Region of Respondents

Regarding statistics, 25 of the respondents were from Pakistan, 05 were from India, 05 from Bangladesh, 06 from Egypt, 04 from South Africa, 05 from Iran, 03 from the Maldives, 05 from Nepal, 03 from Nigeria and 04 from Zimbabwe.

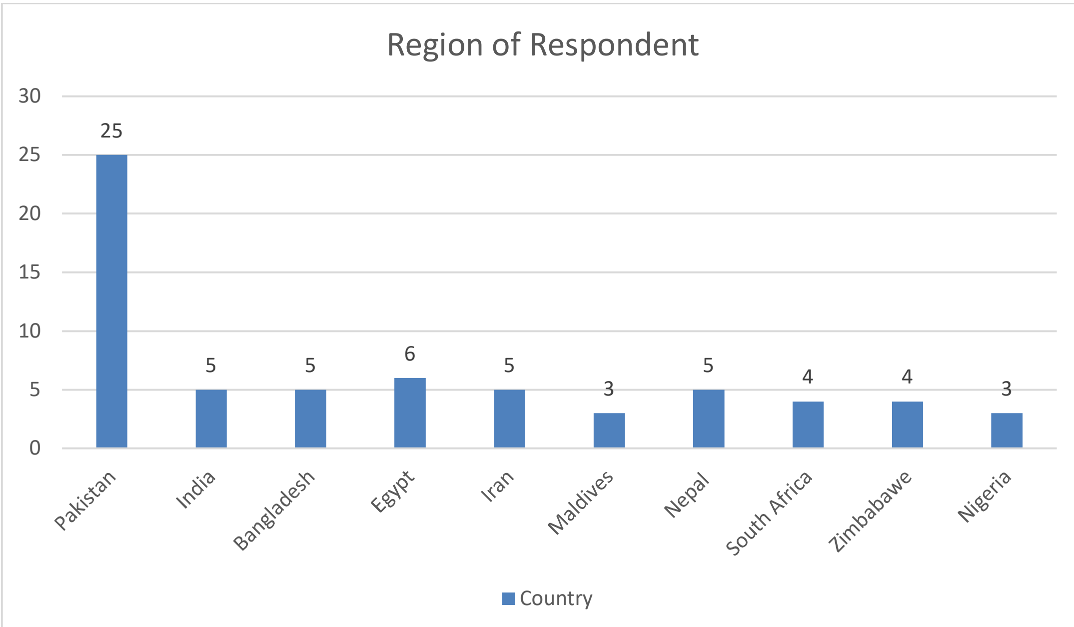

Figure 5: Regions of respondents

4.2.5 Normality and Reliability Check

Cronbach's Alpha test was used to determine the data's reliability and internal consistency. The benchmark value is 0.9, and the higher the number, the more reliable and internally consistent the data is, as shown in Figure. Cronbach's Alpha value was 0.96, indicating that the data was sufficiently trustworthy and internally consistent (Tavakol and Dennick, 2011).

Table V: Cronbach's Alpha Benchmark values

The Relationship between the Cronbach's alpha Value and Internal Consistency	
Cronbach's alpha Value (α)	***Internal Consistency***
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable

Table VI: Reliability statistics

Cronbach's Alpha
0.96

4.3 Influence Matrix for Causal Loop Diagram

The influence matrix was created in accordance with the results of the detailed questionnaire survey, as well as the interpretation and analysis of the data. Values in the matrix represented information gleaned from expert's viewpoints, which helped to modify the causal loop diagram. Expert advice was considered in order to make the causal loop more relevant and confirm that feedback loops are flowing in the same direction. Following that, expert comments and the improved influence matrix is shown below were used to adjust the directions of a few interrelations. Influence matrix produced from relative importance index of finalist elements and causal loop diagrams obtained from important causal relations. Causal relationships with RII values more than or equal to 0.75 or a mean value of 3.75 to 5 are chosen for further investigation. (Chong *et al.*, 2017).

Figure 6: Influence matrix established from the correlation of impacting and impacting effects.

	V1	***V2***	***V3***	***V4***	***V5***	***V6***	***V7***	***V8***	***V9***	***V10***	***V11***	***V12***
V1	1				0.78	0.77			0.79			
V2		1								-0.77		
V3	-0.83		1									
V4				1							0.79	
V5		0.76			1							
V6						1	0.78					
V7			-0.77				1					
V8								1				
V9				0.78				0.78	1			
V10	-0.78									1		
V11	0.77										1	
V12	0.77											1

V1: Waste Minimization V2: Reduction in energy consumption V3: Pollution V4: Facilitation of Green Features V5: Reduction in Carbon Footprint V6: Less Hazardous Waste V7: Lowered Green House Gas Emissions V8: Less Hidden waste V9: Improvement of Environmental Quality V10: Fuel consumption V11: Reduction in Water Consumption V12: Minimized Wastage of Material in stock

Y-Axis = Impacted Effects X-Axis = Impacting Effects

4.4 Causal Loop Diagram

A causal loop diagram (CLD) is created in accordance with interrelationships that have mean influence values ranging from 3.75=<m<=5. It has two reinforcing loops and two balancing loops. To make it less complicated and meaningful, the CLD is created in collaboration with construction specialists with over 10 years of expertise. The following stage was to ensure that feedback loops were revolving in the same direction and that any interrelations that were leading away from the system were not neglected (Dhirasasna and Sahin, 2019) . The CLD is constituted of two reinforcing and two balancing loops and each loop is elaborated step by step.

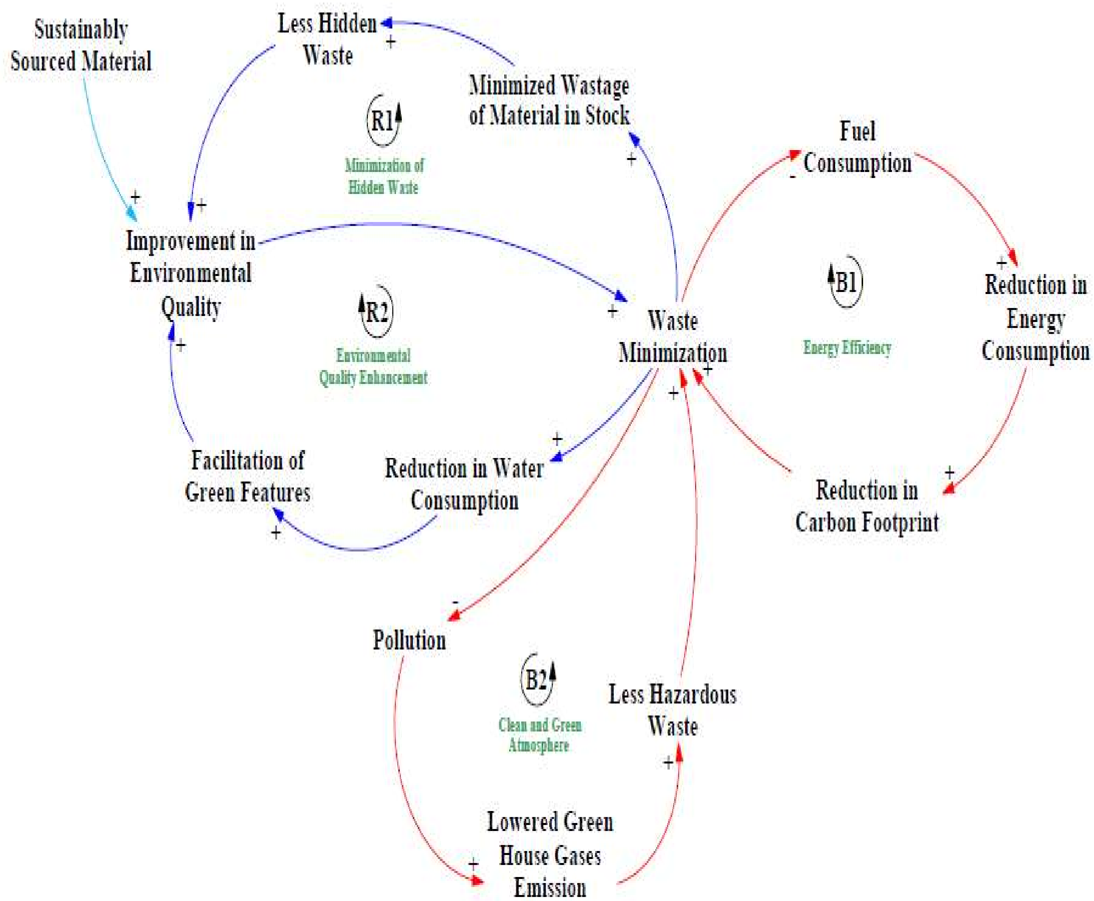

Figure 7: Causal Loop Diagram(CLD).

4.4.1 Energy Efficiency Loop

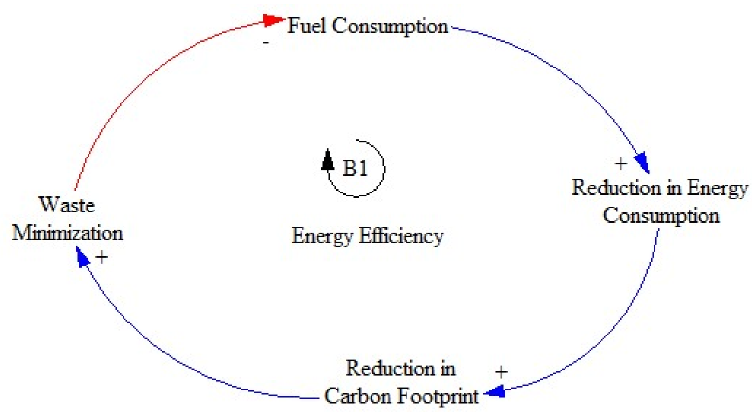

Figure 8: Balancing Loop B1

Loop B1 in Figure 8 shows that increased waste minimization results in the reduction of fuel consumption. Most of the energy consumed in construction processes is generated by fossil fuels. This results in a high amount of carbon emissions which accumulatively increase the carbon footprint. By decreasing fuel consumption, the reduction of energy consumption takes place which finally leads to a reduction in carbon footprint. Here we can consider the type of lean waste that is defective work (Defects) which needs to be rectified or abandoned. It generates direct material waste, pollution, and energy consumption because of raw material loss and indirectly leads to carbon emissions because of operations. Therefore, this loop holds a robust influence that is recognized to be self-balancing.

4.4.2 Clean and Green Environment Loop

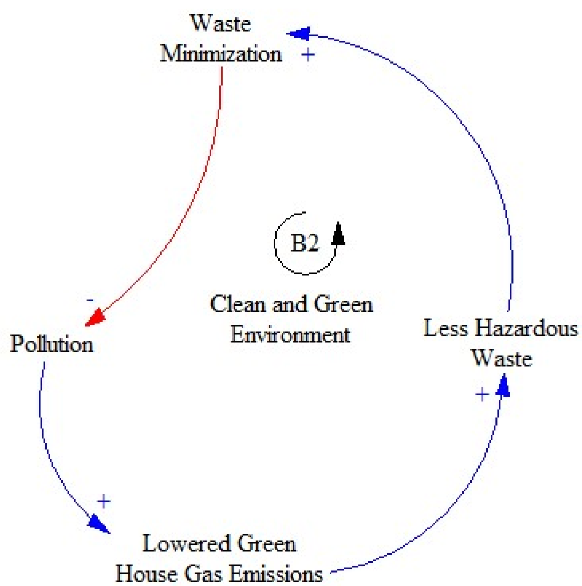

Figure 9: Balancing Loop B2

The loop B2 shown in the figure 9 implies that increased minimization of waste results in a decrease in pollution which further leads to a reduction of greenhouse gas emissions. Pollution also constitutes hazardous greenhouse gases which are emitted by construction equipment and machinery. By reducing them we are reducing the overall generation of hazardous waste. Here we consider the types of lean waste that are excessive transportation or motion, due to inadequate site layout and logistics impact the environment directly by generating pollution, particulate matter and greenhouse gases. All of this type of waste contributes to hazardous waste in the environment.

4.4.3 Minimization of Hidden Waste Loop

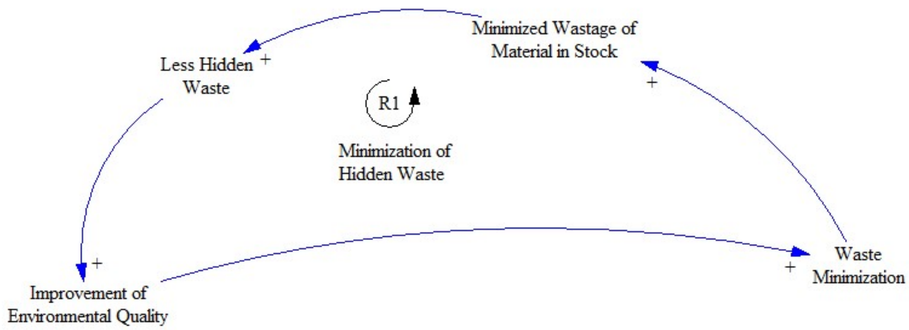

Figure 10: Reinforcing Loop R1

The loop shown in the figure 10 implies that the amplification in the minimization of waste resulted in an increase in the reduction of hidden waste. In construction sites, most of the hidden waste is produced due to wastage of material in stock. Minimization of wastage of material in stock results in less generation of hidden waste. Here we consider the type of lean waste that is excessive inventory which could lead to inadequate storage and space constraints. This can lead to material waste due to spillage or deterioration indirectly causing pollution, excessive energy expenditure and raw material loss. Hence the environmental quality gets affected.

4.4.4 Environmental Quality Enhancement Loop

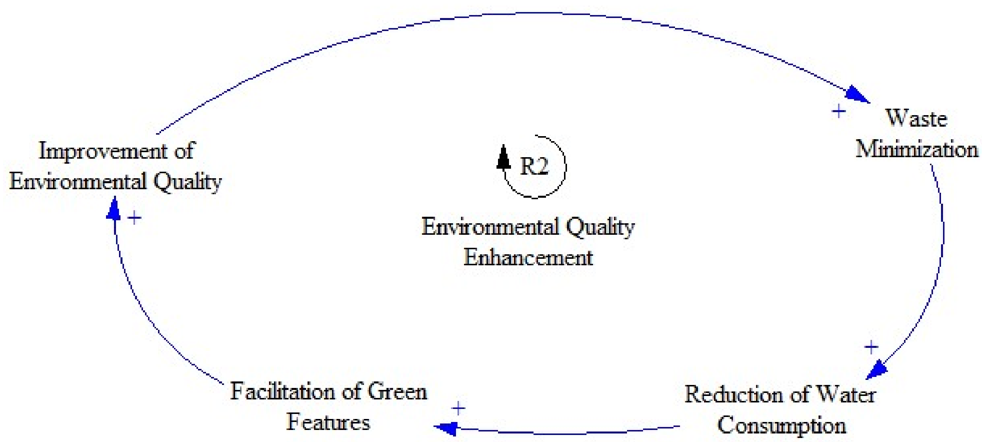

Figure 11: Reinforcing Loop R2

The loop shown in the figure 11 implies that an amplification in the minimization of waste leads to a reduction in water consumption and facilitates green features in the construction phase. The less or efficient use of water is a very important part of the green construction concept. This also leads indirectly to less energy consumption which also supports the green construction concept. Here we can consider the types of lean waste that are overproduction and extra-processing which directly result in excessive consumption of energy, water and material waste and could lead to additional raw material extraction due to the making of unwanted quantities or components and indirectly polluting the environment.

4.5 System Dynamics Model

The System dynamics model was developed from the causal loop diagram. Waste minimization and improvement of environmental quality were the two main stocks identified and the additional stock was also incorporated in the model expressed as environmental sustainability to observe the convergence of the existing two stocks. The relative importance index is calculated by using the mean value. Following that, because the nature of the inquiries was not distinct and unconnected, the mean value was picked instead of the mode value. (Tahir, Khan and Nasir, 2021). Consequently, 16 causal relationships were shortlisted having RII greater or equal to 0.75.

$$\textbf{Mean Value} = {(\mathbf{1} * \textbf{Low} + \mathbf{3} * \textbf{Medium} + \mathbf{5} * \textbf{High})}/{\textbf{Number of respondents}}$$

Eq.2

$$\textbf{(RII)} = (\textstyle\sum \mathbf{W})/(\mathbf{A} * \mathbf{N}) \qquad \textbf{Eq.3}$$

W = weightage given on Likert Scale

A = maximum weightage on Likert Scale,

N = total number of participants, and

The RII has a minimum value of 0 and maximum value of 1.

Table VII: Correlation, polarity and relative importance index of finalist causal relationships.

Sr. No.	Impacting Effects	Impacted Effects	Mean	RII	N. RII	Polarity
1	Reduction in Energy Consumption	Reduction in Carbon Footprint	3.80	0.76	0.0611	Direct
2	Pollution	Lowered Greenhouse gas emissions	3.86	0.77	0.0621	Indirect
3	Less Hidden Waste	Improvement of Environmental Quality	3.92	0.78	0.0630	Direct
4	Reduction in Water Consumption	Facilitation of Green Features	3.95	0.79	0.0635	Direct
5	Fuel consumption	Reduction in energy consumption	3.83	0.77	0.0616	Indirect
6	Lowered Greenhouse gas emissions	Less Hazardous Waste	3.89	0.78	0.0625	Direct
7	Improvement of Environmental Quality	Waste minimization	3.95	0.79	0.0635	Direct
8	Less Hazardous Waste	Waste minimization	3.83	0.77	0.0616	Direct
9	Reduction in Carbon Footprint	Waste minimization	3.89	0.78	0.0625	Direct
10	Waste minimization	Pollution	4.14	0.83	0.0666	Indirect
11	Waste minimization	Fuel Consumption	3.88	0.78	0.0624	Indirect
12	Waste minimization	Minimized Wastage of Material in stock	3.83	0.77	0.0616	Direct
13	Sustainably Sourced Material	Improvement of Environmental Quality	3.85	0.77	0.0619	Direct
14	Minimized Wastage of Material in stock	Less Hidden Waste	3.86	0.77	0.0621	Direct
15	Facilitation of Green Features	Improvement of Environmental Quality	3.89	0.78	0.0625	Direct
16	Waste minimization	Reduction in Water Consumption	3.83	0.77	0.0616	Direct

The equations developed through normalized mean influence for inflows and outflows of all stocks are given below:

1. **Waste Minimization inflows** = 0.0625*V5 + 0.0616*V6 + 0.0635*V9 + 1*V1 **Eq.4**

2. **Waste Minimization outflows** = 1*V1 **Eq. 5**

3. **Improvement in Environmental quality inflow** = 0.0625*V4 + 0.0630*V8 + 1*V9

   Eq. 6

4. **Improvement in Environmental quality outflow** = 1*V9 **Eq. 7**

5. **Environmental Sustainability inflow** = V1 + V9 + 1*ES **Eq. 8**

6. **Environmental Sustainability outflow** = 1*ES **Eq. 9**

V1: Waste Minimization V2: Reduction in energy consumption V3: Pollution V4: Facilitation of Green Features V5: Reduction in Carbon Footprint V6: Less Hazardous Waste V7: Lowered Green House Gas Emissions V8: Less Hidden waste V9: Improvement of Environmental Quality V10: Fuel consumption V11: Reduction in Water Consumption V12: Minimized Wastage of Material in stock ES: Environmental Sustainability (Additional Stock)

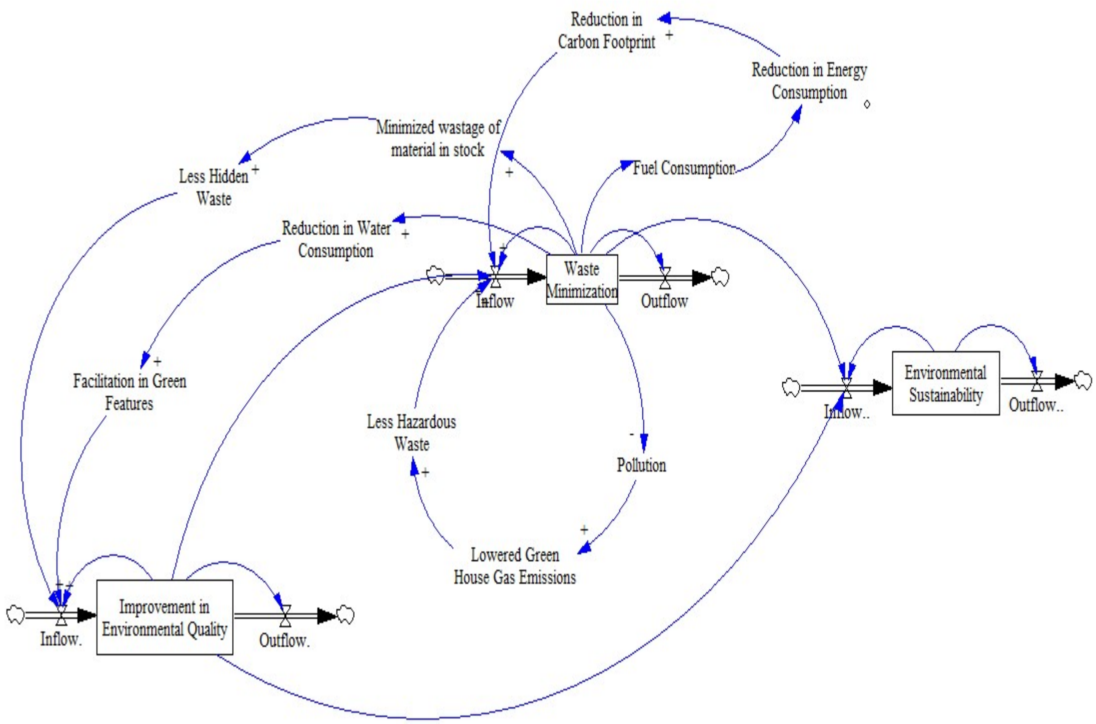

Figure 12: System dynamics model

4.6 Simulation and Results

This simulations are representing the behavior of the complex interconnected system and two stocks termed waste minimization and improvement in environmental quality were simulated distinctly over the period of five years. Subsequently, an additional stock expressed as environmental sustainability was simulated to determine the impact of two stocks, which converged on it.

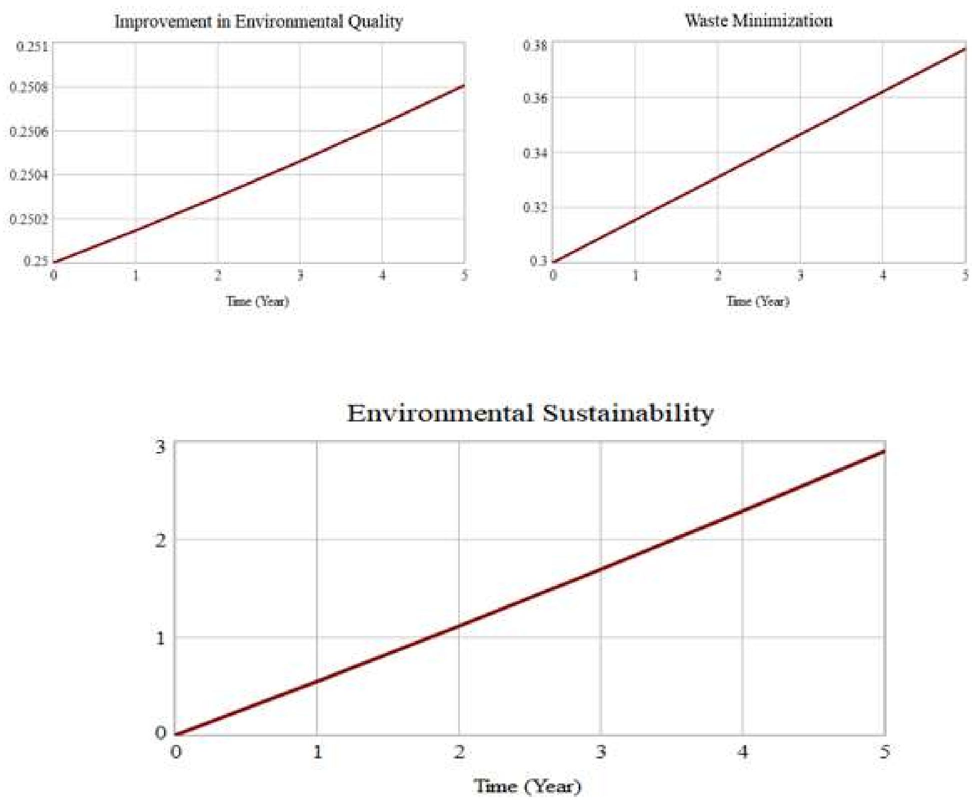

Figure 13: Simulation graph (Behaviour of stocks)

The graphs shown figure 13 are depicting that by using lean construction practices we are basically reducing waste (lean waste) and improving environmental quality which further leads to a sustainable environment. Minimization of waste (lean waste) directly and indirectly results in a reduction in multiple factors like energy consumption, pollution, hazardous waste and carbon emissions. All these factors are directly proportional to environmental sustainability. Hence the goal of a sustainable environment can be seen as affected positively by the adoption of lean construction.

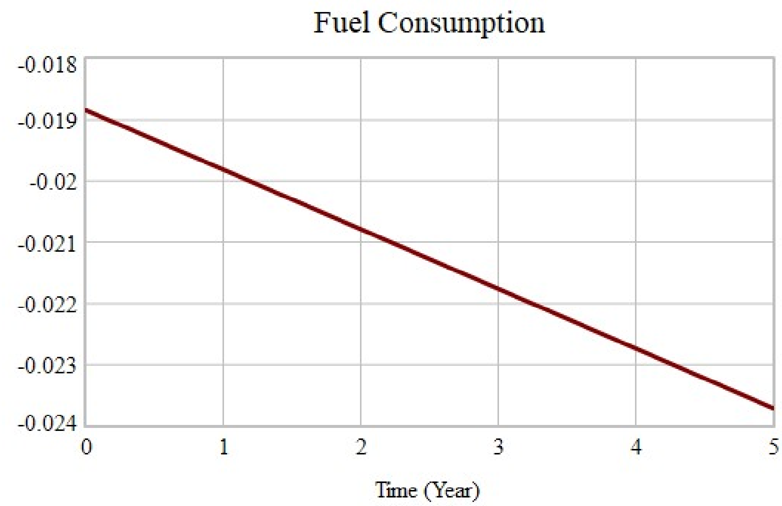

Figure 14: Simulation graph (Fuel Consumption)

The graph shown in figure 14 shows that fuel consumption decelerates as waste minimization accelerates. Since the emissions resulted by burning of fossil fuels are considered one of the biggest hazards to the environment. Reduction in consumption of fuel results in minimized carbon footprint and energy consumption. The conservation of energy and less release of emissions leads to a sustainable environment. Consequently, the simulation graph of fuel consumption and pollution extrapolated declining behavior over the course of five years.

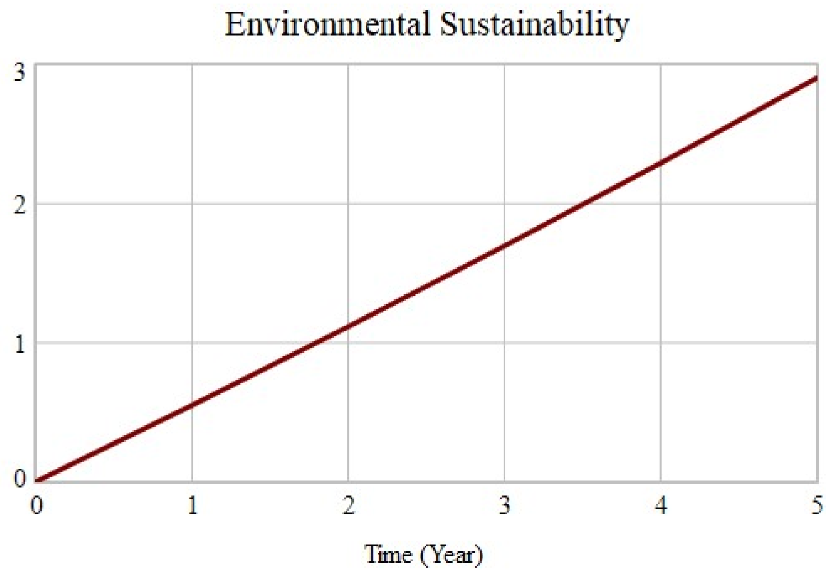

Figure 15: Simulation graph (behaviour of environmental sustainability over the course of five years)

The graph shown in figure 15 deduces that lean construction has affected environmental sustainability positively over the course of five years. The minimization of waste, energy and resources led to relentless improvement in the environmental quality. Consideration of these effects deduced by lean construction can result in a much more sustainable environment. This simulation is showing the effects of lean construction on environmental sustainability over a period of five years.

4.7 Model Validation

The aim for which the system dynamic was produced was the main point for validation. The key idea of the system dynamic model was to assess the effects on environmental sustainability that resulted from the introduction of lean construction philosophy in developing nations construction industries. The following tests were conducted to validate the system dynamic model (Tahir, Khan and Nasir, 2021).

1. **Boundary Adequacy Test**
2. **Structure Verification Test**
3. **Parameter Verification**

1. ***Boundary adequacy test*** was carried out to support three factors: if all relevant discoveries are endogenous to the system or not, whether model change behavior is significant as boundary circumstances change, and whether policy suggestions change when the boundary is expanded. In the current model, all variables are endogenous to the system. Consequently, after simulation, the behavior of the model and policy recommendations does not alter when boundary conditions are altered.

2. ***Structure verification test*** was carried out to make sure that the structure of model is consistent and logical. All relevant factors in the current system dynamic model were reviewed through a thorough literature research and cross checked by construction industry professionals. Finalist causal linkages and polarities were used to draw out the resulting causal loop diagram, which was then amended as per expert's viewpoints. As a result, the system dynamic model is useful, aware, logical, and precise in its representation of specific construction industry systems. This practice is in compliance of effort carried out by (Qudrat-Ullah and Seong, 2010).

3. ***Parameter verification test*** showed that the mathematical functions contained in the system dynamic model were constructed based on two essentials: causal strength and polarity of interrelations, it was extrapolated. The construction professionals assessed the causal strength and polarity of finalist interrelations.

Chapter 5

CONCLUSION

Lean construction challenges conventional construction thinking and provides a strong theoretical foundation for solutions to solve the complications in the construction industry that are related to the environment. The aim of this research work was to assess the effects of lean construction on environmental sustainability, especially in developing countries. The system thinking approach was used to simplify the complex causative interaction between lean construction and environmental sustainability by the development of a system dynamics model that led towards distinguishing it.

A precise and conclusive literature review was conducted and twenty-eight effects were extracted. Preliminary and detailed surveys were conducted and cumulative normalized literature and industry scores were determined by statistical tools. A pilot survey was initiated to screen out the least significant effects and a detailed survey was conducted to determine their causal relationship and polarity either direct or indirect.

A preliminary survey was conducted by circulating a questionnaire form developed through **Google®** and respondents were asked to rank the effects on the Likert scale. The detailed survey was conducted to evaluate causal relationship strength, and polarity either direct (+) or indirect (-) and subsequently, the relative importance index (RII) of each shortlisted relationship was determined. The influence matrix is illustrated by the causal interrelationship of impacting factors and impacting factors having a mean value ranging from **3.75<=m<=5**.

Waste Minimization, Reduction in Energy Consumption, Less Hidden Waste, Facilitation of Green Features and Reduction in Carbon Footprint are considered the major effects of lean construction on environmental sustainability.

In accordance with the opinions of experts in construction field and significant shortlisted interrelationships, the causal loop diagram (CLD) was developed. Expert opinions and valuable suggestions were necessary to make the causal loop diagram more significant and relevant to the need and demands of the construction sector.

The system dynamics model was created by connecting causal relationships and polarities, and it was then validated by applying tests. ***Waste Minimization and Improvement in environmental quality*** were specified as two notable stocks of this system dynamics model. The third stock termed ***environmental sustainability*** was additionally incorporated and other two existing stocks were converged on it to show their combined effect.

The evolution of a system dynamics model was aided by the use of a combination of an influence matrix, a causal loop diagram and finally drawn on **VENSIM® Software.** This model was simulated over a time of five years. Under the influence of reinforcing interrelationships, the existing two accumulated stocks showed ascending behavior throughout time. The graph of effects of lean construction on environmental sustainability including ***fuel consumption and pollution*** exhibited descending trend over the course of time as these are negatively complemented by waste minimization. Subsequently, the ***environmental sustainabilit****y* graph illustrated ascending behavior over the period as the two stocks converged on that point. This reflected the fact that lean construction has made positive effects on environmental sustainability as the years passed under a well-defined system.

The causal loop diagram and system dynamics model holistically explicated the effects of lean construction on environmental sustainability through the systems thinking approach. The findings of this exploration work strengthen the foundation of implementing a lean construction approach in the construction sector for minimizing the negative impacts on the environment.

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