Non-Physical Construction Waste Quantification and Optimization Using Lean Construction Principles

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This is to certify that the
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THESIS ACCEPTANCE CERTIFICATE

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This thesis is dedicated to people who kept me motivated even when I wanted to give up!

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In the name of Almighty Allah, the most Merciful, the Beneficent. All praise is only for Allah who created us and always planned the best for us. I am grateful to the Almighty Allah for His countless blessings and mercy bestowed upon me through the difficulties of life and I seek His guidance, and pray to Him for blessings and ease throughout this life and the life to come.

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Abstract

A construction project comprises of conversion and flow activities; conversion activities are value adding, and flow activities are non-value adding and generally contribute into non-physical waste (NPW). Unlike material waste, NPW impacts both time and cost. Lean construction can monitor and control this waste. Though lean practices in construction have shown remarkable improvements, NPW quantification is still not possible. To address this deficiency, current research identifies the key macro and micro level factors contributing into NPW and develops a system dynamics (SD) model using the interrelationships between these factors. The simulation results reveal that under four constant exogenous factors, 21% NPW is generated in a 24-month project. Further, the scenario based simulation highlights that lean construction can provide observable reduction in NPW. The developed model can improve the management practices by providing a comprehensive understanding of NPW, which in turn can help mitigating its impact on project progress.

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NPW	Non-physical waste
SD	System dynamics
CLD	Causal loop diagram
LPS	Last planner system

Chapter 1

1 INTRODUCTION

1.1 Overview

Construction industry due to its dynamic nature and continuous development has brought with it some problems like waste. In general there are two schools of thought while defining construction waste: some define it as the surplus and damaged products and materials produced during new construction, renovation and demolition of buildings (Kofoworola and Gheewala, 2009), while others include non-value adding activities in the basic definition (Hosseini et al., 2012, Alwi et al., 2002a). Further, Serpell and Alarcón (1998) defined waste as *"all construction activities that produce cost, direct or indirect, but do not add value or progress to the product"* and Womack and Jones (2010) defined waste as *"any human activity which absorbs resources but creates no value"*. Thus, researchers have divided construction waste into physical and non-physical categories (Khanh and Kim, 2014).

Construction waste usually occurs during the execution phase of the project but it is due to a set of events happening at design, construction and procurement phases (Nagapan et al., 2012). Different methods and philosophies have been employed by researchers over the years for waste minimization and recently the concept of lean construction to achieve sustainability is at its escalation. Though lean construction principles which are employed from manufacturing industry are still new to the construction industry, its main technique of waste reduction can be applied to increase productivity (Hosseini et al., 2012).

The application of lean construction is a strategic decision when it has to be implemented in new locale. Senaratne and Wijesiri (2008) conducted a study to check the suitability and acceptability of lean construction in Sri Lanka and found that local workforce was not aware of the activities that cause non-physical waste such as unnecessary movement of material and labor, damaged material, waste due to waiting periods and rework. Further, it is found that frequent design changes, poor material handling & storage, poor attitude of workers, poor site conditions, lack of waste management plan and material procurement are the main causes of non-physical waste during construction projects (Nagapan et al., 2012).

Green and May (2005) categorized lean construction concept as: waste minimization, partnerships to improve relationships, and structural changes in design and construction processes. Restructuring design and construction procedures means the use of technological advancements like computer aided designs (3D modelling) and prefabrication to reduce waste. Offsite manufacturing of building components and units is a key towards construction waste reduction by reducing the construction duration and providing more controlled environment for the production of units and making lean construction similar to lean production in manufacturing industry (Segerstedt et al., 2010).

At present not much work has been carried out on the subject. Hosseini et al. (2012) used event simulation based on lean thinking to determine the optimization potential in construction processes but the study was based on one single event, hence no quantitative results were achieved. This study focuses on non-physical waste reduction element of lean construction. Most significant factors contributing to non-physical waste are identified, further quantification of non-physical waste produced in building projects be carried out and finally lean construction techniques are applied as mitigation strategies. Help from already published literature and feedback from experienced field professionals was used to achieve the objectives of this study.

1.2 Problem Statement

Construction processes have high potential of optimization by implementing lean construction principles to reduce waste (Hosseini et al., 2012). Prevention of waste must begin at the very first moment with the award of contract. A distress in construction waste management is caused by lack of research, and absence of quantifiable and justifiable solution as no practical method in construction industry is available to quantify non-physical waste produced during a project (Alwi et al., 2002a). The non-value adding activities in construction processes bring a great deal of opportunities for applying lean construction principles if corresponding changes in construction operations are made.

1.3 Research Objectives

Following are the specific objectives of this research:

i. To identify the most significant factors causing non-physical waste in a construction project as a result of non-value adding activities.

ii. To develop a system dynamics model using interrelationships between the identified factors.

iii. To quantify non-physical waste in building projects using scenario based simulation and provide mitigation strategies.

1.4 Scope of Study

This research is limited to building projects only, as field experts with experience in building projects are only contacted for data collection.

1.5 Significance of Study

By deriving an approach towards non-physical waste quantification and reduction using lean construction principles, this research will help the stakeholders to have better monitoring and control strategies as non-physical waste is one of the most significant causes to time and cost overrun. It will also address the associated problems like delays due to improper material handling and improper material management due to poor inventories.

1.6 Relevance to National Needs

Although the construction sector has only a 2.3 percent share in GDP, its share of the employed labor force is disproportionately large in Pakistan. It provides jobs to about 5.5 percent of the total employed labor force or 2.43 million people (2.41 million male and 0.2 million female) (Khan, 2008). But it is also the industry that consumes a higher proportion of mineral resources excavated from nature and generates substantial portion of atmospheric CO_2 and contributes the largest volume of landfill waste. Quantifying non-physical waste will enable Pakistan's construction industry to have better managed construction processes, hence more control on material waste which will ultimately lead to achieving environmental sustainability, as construction industry of a developing country has been a target for the global sustainability agenda.

1.7 Thesis Overview

This thesis has been organized into five chapters.

Chapter 1 is '*Introduction*'. It includes an overview to the research, problem statement, objectives and scope of the study. It provides a general introduction to the research.

Chapter 2 is '*Literature Review'*. It explains the previous studies carried out concerning the research providing essential information and guidelines to cater the problems of waste management in construction.

Chapter 3 is '*Methodology*' of research. It explains how the research has been carried out to obtain our objectives.

Chapter 4 is '*Results and Discussion'* that covers the analysis of data.

Finally, *Chapter 5* is '*Conclusions and Recommendations'* where final conclusions and recommendations have been summarized.

Chapter 2

2 LITERATURE REVIEW

2.1 Waste in Construction

In general waste in construction is associated with material waste. Research reveals that 1 to 10 % of the material purchased during construction project is wasted (Bossink and Brouwers, 1996). A total of 89.6 million tons of construction waste was generated in 2005 in UK (DEFRA, 2011) and in US 534.1 million tons of construction waste was produced in 2014 (EPA, 2016). According to Building Research Establishment UK up to £130 million can be gained by reducing construction waste in UK by 5% only (BRE, 2003), therefore over the years researchers have made efforts to reduce construction material waste and achieve financial and environmental benefits.

Another type of waste studied in recent years is the non-physical waste. Koskela (1992) defined non-physical construction waste as *"activity that takes time, resources or space but does not add value"*. It is also defined as the duration of construction activity as sum of process time, inspection time, move time and wait time. Hence, only value adding activity is the process time, while the rest are considered as non-value adding activities. However, some processes are also subjected to waste resulting from defective work, lower productivity due to unskilled labor, overproduction and incorrect application of construction methods (Pheng and Tan, 1998).

2.2 Non-physical Waste in Construction Industry

Waste is one of the major problems in the construction industry, and where material waste immensely effects the cost of the project, non-physical waste causes both time and cost overruns (Senaratne and Wijesiri, 2008, Hosseini et al., 2012, Polat and Ballard, 2004). Generally project managers are keen in reducing the production cost during project execution phase while giving little or no attention to the cost of non-physical waste produced due to non-value adding activities (Saukkoriipi, 2004). Cost of non-value adding activities and its lack of knowledge creates problems for the stakeholders as most of this cost is unknowingly shifted to contingency reserves (Ndihokubwayo and Haupt, 2009).

Though material contribute to 50-60% of the total project cost (Ibn-Homaid, 2002, Kong et al., 2001), a study by Ramaswamy and Kalidindi (2009) in India exhibited that waste due to non-value added activities by labor and equipment was much higher compared to material waste generated on the sites.

2.3 Factors Causing Non-physical waste

A detailed literature review of published articles provided us with overall 16 factors which contribute towards the non-value adding activities in the form of non-physical waste.

Table 2.1: Factors causing non-physical waste

S. No	Factors Causing Non-physical Waste	REFERENCES
1	Design changes/Variations	Han et al. (2011), (Serpell et al., 1995, Osmani et al., 2008, Alwi et al., 2002a, Alwi et al., 2002b, Ndihokubwayo and Haupt, 2009, Wu et al., 2013, Josephson and Saukkoriipi, 2003, Zhao and Chua, 2003, Garas et al., 2001, MEMON et al., 2016, Nagapan et al., 2012)
2	Errors	(Han et al., 2011, Serpell et al., 1995, Osmani et al., 2008, Garas et al., 2001, Lee et al., 2007)

3	Decision making process	(Alwi et al., 2002a, Nahmens and Ikuma, 2011, Lee et al., 2007)
4	Labor skills	(Serpell et al., 1995, Alwi et al., 2002a, Alwi et al., 2002b, Ramaswamy and Kalidindi, 2009, Garas et al., 2001, Khanh and Kim, 2015, MEMON et al., 2016, Wu and Feng, 2014, Nagapan et al., 2012)
5	Poor site documentation and Layout	(Alwi et al., 2002b, Wu and Feng, 2014, Nagapan et al., 2012)
6	Slow drawing revision	(Alwi et al., 2002b)
7	Delays	(Serpell et al., 1995, Osmani et al., 2008, Alwi et al., 2002a, Alwi et al., 2002b, Nahmens and Ikuma, 2011, Rosenbaum et al., 2013, Arroyo and Gonzalez, 2016, Khanh and Kim, 2014, Garas et al., 2001)
8	Waiting periods (instructions, material & equipment)	(Alwi et al., 2002a, Serpell et al., 1995, Formoso et al., 1999, Rosenbaum et al., 2013, Arroyo and Gonzalez, 2016, Khanh and Kim, 2014, Zhao and Chua, 2003, Ramaswamy and Kalidindi, 2009, Garas et al., 2001, Ohno, 1988, Wu and Feng, 2014)
9	Overtime	(Serpell et al., 1995, Hanna et al., 2005)
10	Over manning	(Nahmens, 2009, Formoso et al., 1999, Arroyo and Gonzalez, 2016, Khanh and Kim, 2014, Ohno, 1988)
11	Inventory	(Nahmens, 2009, Formoso et al., 1999, Rosenbaum et al., 2013, Zhao and Chua, 2003, Ramaswamy and Kalidindi, 2009, MEMON et al., 2016, Ohno, 1988, Wu and Feng, 2014)
12	Logistics (unnecessary movement of labor & equipment)	(Nahmens, 2009, Formoso et al., 1999, Khanh and Kim, 2014, Garas et al., 2001, Khanh and Kim, 2015, Ohno, 1988)

13	Processes	(Nahmens, 2009, Serpell et al., 1995, Formoso et al., 1999, Josephson and Saukkoriipi, 2003, Khanh and Kim, 2014, Lee et al., 2007, Khanh and Kim, 2015, Ohno, 1988)
14	Workflow reliability	(Thomas et al., 2003, Rosenbaum et al., 2013, Arroyo and Gonzalez, 2016, Zhao and Chua, 2003, Khanh and Kim, 2015)
15	Defective production	(Formoso et al., 1999, Josephson and Saukkoriipi, 2003, Nahmens and Ikuma, 2011, Arroyo and Gonzalez, 2016, Khanh and Kim, 2014, Ramaswamy and Kalidindi, 2009, Garas et al., 2001, MEMON et al., 2016, Wu and Feng, 2014)
16	Injuries	(Josephson and Saukkoriipi, 2003, Khanh and Kim, 2014)

2.4 Lean Construction

The root of 'lean' production system lies in the management philosophy of Toyota Production System (TPS) developed by Taiichi Ohno, and since early 1990's has been adopted by the construction industry to increase productivity by minimizing waste. Koskela (1992) developed a new production theory applicable to construction industry and argued that waste activities like waiting, storing inventory, material and equipment movement, and inspection are not highlighted by control tools such as critical path method (CPM), where emphasis is only on value adding (conversion) activities and not on flow activities. Hence the concept of lean construction came into existence where construction processes are considered to include both value adding activities and non-value adding activities but the emphasis being on removing and minimizing the non-physical waste (non-value adding activities) (Hosseini et al., 2012).

Segerstedt et al. (2010) classified lean construction management into six core elements: waste reduction, process focus in production planning and control, end customer focus, continuous improvements, cooperative relationships, and systems perspective. Further Green and May (2005) categorized lean construction concept as: waste reduction, relationship improvement, and fundamental changes in design and construction processes. Over the years, a lot of research effort has been carried out to use waste reduction, the core attribute of lean construction to decrease waste and increase process productivity. This process improvement tool is referred to as 'kaizen' by TPS which means continuous improvement. Kaizen pursues construction process optimization by eliminating non-physical waste (non-value adding activities) from the viewpoint of a customer (Nahmens and Ikuma, 2011). Non-physical waste reduction is the key attribute of lean construction by decreasing delays due to inspection, logistic and material flow interruption (Mao and Zhang, 2008).

Successful application of lean construction means significant reduction in cost associated with non-value adding activities, decreasing overall project cost and increasing profitability (Senaratne and Wijesiri, 2008). A study by Erol et al. (2017) using probabilistic analysis depicted an overall 6.15-9.56% percent decrease in project duration when lean construction principles were applied to a residential building. Lean construction also helps in the work flow (availability of material and equipment) management and can improve labor efficiency hence reducing waste in the form of time overruns. Thomas et al. (2003) determined that ineffective flow management of both workflow and labor flow caused an overall 51% of labor inefficiency equal to 76 crew workdays.

Further Nahmens (2009) found that with application of lean construction principles together with green building concept of industrialized modular buildings, a total of 12% can be saved on equipment waste by reducing the space required for operations, 10% material waste and reducing the workforce from 9 to 6.5 people (labor waste).

2.4.1 Application of Lean Construction Phenomena

There are three main steps in which lean construction phenomena works, waste elimination, relationship improvements for long term contracts and the use of IT tools to develop structural and design changes (Green and May, 2005). The central focus of all three steps is on eliminating activities that produce non-physical waste in the form of unnecessary movements of material, labor and equipment, delays due to waiting for material and equipment to arrive and excess inventory (Arroyo and Gonzalez, 2016, Rosenbaum et al., 2013, Zhao and Chua, 2003, Khanh and Kim, 2014).

This operational efficiency can be achieved by using Just-in-Time (JIT) principle of lean construction. The aim of JIT application is to eliminate wastes from delays, logistics, unnecessary processes and unnecessary stocking of material, as all non-value adding processes are considered as non-physical waste (Pheng and Tan, 1998). The use of JIT delivery system and prevention of excess stocking are important non-physical waste reduction strategies (Ajayi et al., 2017)

Lean construction practices are greatly influenced by workflow (movement of material, information and equipment) variability as delay in one activity can effect overall project completion time (Thomas et al., 2003). Last planner system (LPS) is workflow control tool that works under a principle of look ahead planning, where activities are dropped into typically 6-week look ahead windows and are thoroughly checked for all potential threats that are to materialize in that plan period. No activity is allowed to start unless detailed threat mitigation strategies are developed and a complete track of completed assignments in the plan period is kept, so that reasons for any failure can be described at the end of a plan period and future improvements can be made (Ballard et al., 2002). Gao and Low (2014) considers LPS as one of the most effective and well-known planning and control systems among lean construction tools.

Further, Erol et al. (2017) applied the concept of LPS together with lean project delivery system to residential buildings and the findings demonstrate that lean construction principles has a high potential of improving project performance by minimizing both project duration and expected completion date variations.

2.5 Significant Factors Causing Non-physical Waste

A detailed literature review provided with a total of 16 factors that cause non-physical waste, as highlighted in Table 2.1. Qualitative analysis using frequency and literature score for each factor determined that, design changes and variations, waiting periods (for instructions, material & equipment), labor skills, delays, and defective product (rework) are the top most significant factors that cause non-physical waste Table 2.2.

Further, aging factor based on the publication year of each research paper is used to incorporate the effect of newly identified factors. However, Spearman's rank correlation coefficient 'ρ' gives a value of 0.5147, showing a very weak correlation Figure 2.1. This means that even including the age factor, top 5 most significant factors remains same, but with a slight difference in the value of ranking.

Table 2.2: Qualitative analysis of identified factors

Rank	Factor	Frequency	Qualitative Score	Age Factor	Literature Score	Normalized Score	Accumulated Normalized Score	Without Age Factor	With Age Factor
1	Design Changes/Variations	12	5	0.9947	59.6802	0.1237	0.1237	1	1
2	Waiting Periods (instructions, material & equipment)	10	5	0.9943	49.7149	0.1031	0.2268	8	8
3	Defective Product (rework)	9	5	0.9961	44.8265	0.0929	0.3197	4	15
4	Labor skills	9	5	0.9952	44.7843	0.0928	0.4126	7	4
5	Delays	9	5	0.9950	44.7744	0.0928	0.5054	15	7
6	Inventory	7	5	0.9945	34.8091	0.0722	0.5776	11	11
7	Errors	6	5	0.9947	29.8406	0.0619	0.6394	2	2
8	Workflow Reliability	6	5	0.9945	29.8339	0.0619	0.7013	10	14
9	Processes	6	5	0.9937	29.8116	0.0618	0.7631	12	13
10	Over manning	6	5	0.9930	29.7893	0.0618	0.8248	13	10
11	Logistics (unnecessary movement of labor & equipment)	6	5	0.9926	29.7769	0.0617	0.8866	14	12
12	Poor site documentation	3	5	0.9962	14.9430	0.0310	0.9176	3	5
13	Decision making process	3	5	0.9949	14.9232	0.0309	0.9485	5	3
14	Injuries	2	5	0.9958	9.9579	0.0206	0.9691	9	16
15	Overtime	2	5	0.9926	9.9256	0.0206	0.9897	16	9
16	Slow drawing revision	1	5	0.9926	4.9628	0.0103	1.0000	6	6

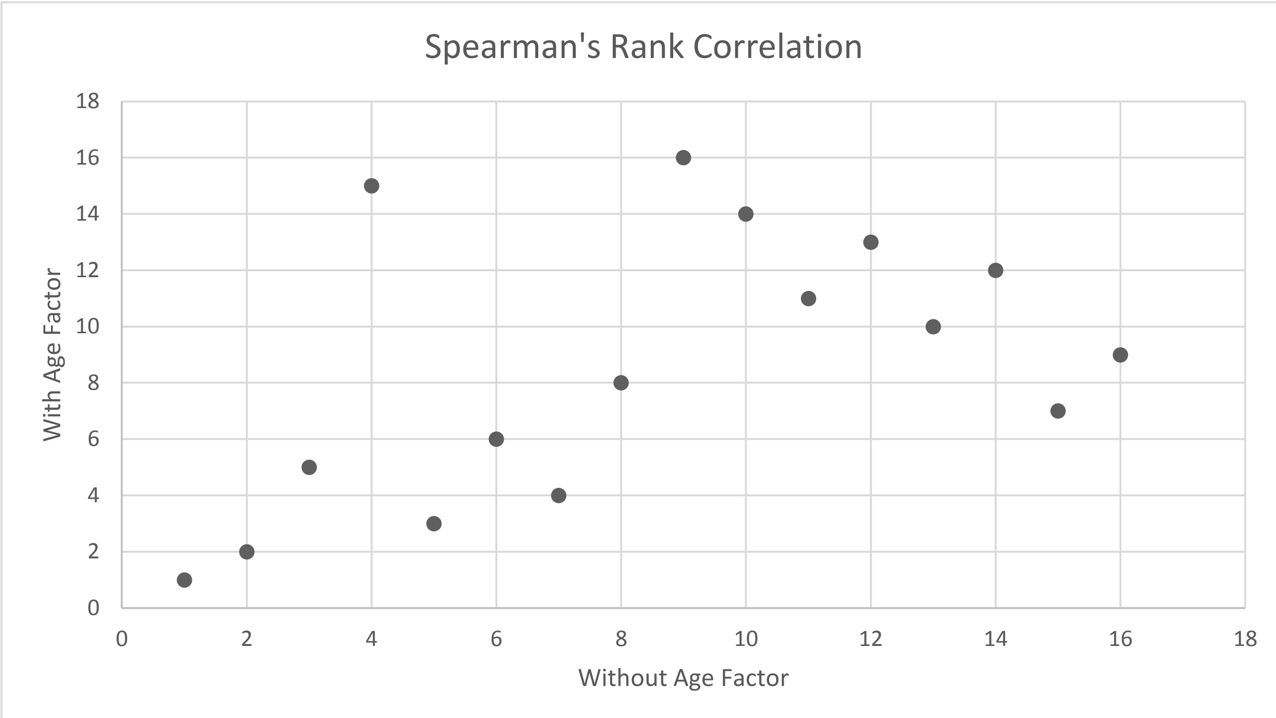

Figure 2.1: Spearman's rank correlation

2.6 Non-physical Waste and its Effect on Project Cost & Schedule

Han et al. (2011) developed a system dynamics model to identify and quantify non-value adding efforts (non-physical waste) due to design changes and errors. The model applied to a bridge project in Massachusetts showed that errors and design changes cause 26% of the non-physical waste and it caused the project a delay of 171 days. On the other hand, Serpell et al. (1995) stated that 53% of total time is focused on activities that are non-productive. Further, Horman and Kenley (2005) found that 49.6% of the construction process time is wasted on non-value adding activities, hence they concluded that an immense amount of potential resides in the construction processes to be optimized for non-physical waste reduction. Whereas a study in Vietnam depicted a mean value of increased project cost due to non-physical waste approximately 9.36% of total project cost (Khanh and Kim, 2014). According to findings by Koskela (1992), 2/3 of project time is utilized by non-value adding activities.

2.7 System dynamics

System Dynamics (SD) was developed by Forrester (1961) to comprehend the dynamics of nonlinear complex systems using stocks, flows, information, delays and internal feedback (Dangerfield et al., 2010). A causal or feedback loop diagram between systems components is constructed which further evolves to stock and flow model which is then run as a computer simulation. SD approach has the ability to address real-world issues by creating 'micro worlds' in a more simple, practical and structurally comprehensive manner. The strength is in the ability to breakdown complex systems into logical sub-systems. SD reports complexity and process interdependence based on non-linear feedback systems (Khan et al., 2015).

In recent years, SD models have been widely used in fields such as environment, and social, business and biosciences as well as engineering. Waste management researchers have developed SD models to quantify and assess waste reduction potential. Han et al. (2011) developed a macro level SD model to quantify the amount of non-value adding efforts produced as a result of errors and design changes. The study revealed that 26% of efforts are wasted on site as a result of non-value adding activities. But this study only considered errors and design changes as the triggering source of non-physical waste. Therefore, current study uses all 16 factors identified from literature, comprising of macro level factors such as rework, errors, variations, etc., and micro level factors like waiting periods, drawing revision time and poor site documentation to develop an SD model using interrelationships between factors and their impact on non-physical waste.

Chapter 3

3 RESEARCH METHODOLOGY

This study focuses on quantification of non-physical waste produced as a result of non-value adding activities. Additionally, significant factors causing non-physical waste and appropriate waste reduction strategies using lean construction principles are also provided. Flowchart of the research design is given in Figure 3-1. To achieve these research objectives, an extensive literature review was conducted to identify factors causing non-physical waste. It was followed by a two-stage data collection process, where in first stage an influence matrix was developed and then converted to a causal loop diagram (CLD), and in the second phase quantitative data was collected using questionnaire survey for system dynamics modelling. Lastly discussion on developed model is done and recommendations are provided.

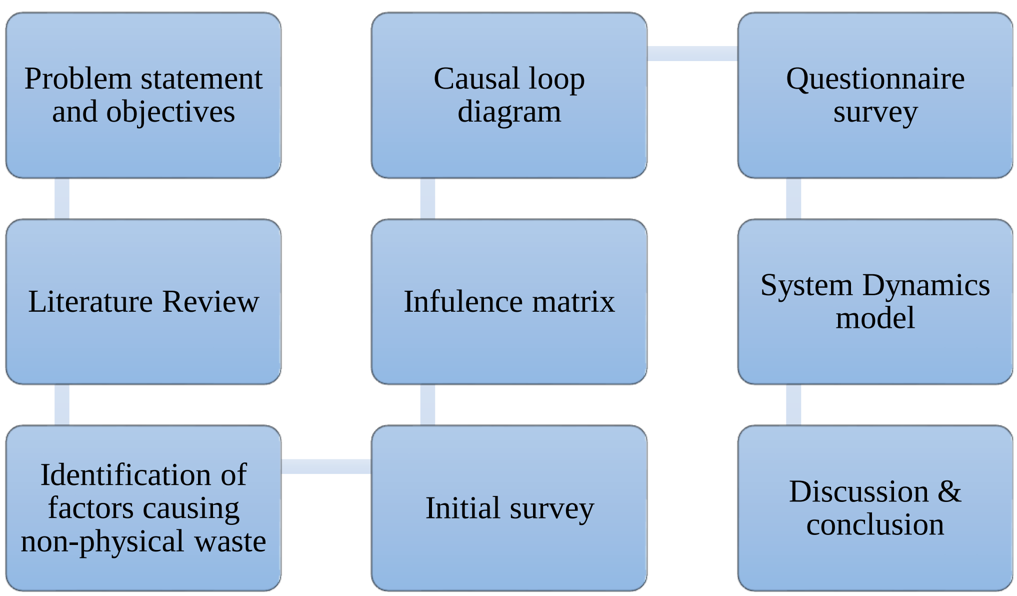

Figure 3-1: Flowchart of research methodology

3.1 Identification of significant factors

Over 80 research papers were collected with publication dating between years 1988-2017 out of which only 24 were found relevant. From these 24 papers, a total of 16 factors that causes non-physical waste were extracted. To rank the identified factors, a mixed method analysis using frequency of appearance (*n*) as a quantitative score and contextual importance as a qualitative score was performed. The frequency (*n*) of each factor was simply noted and cumulated and the qualitative importance was assessed by using the impact of a factor described in the paper. Such as, in the study of Alwi et al. (2002a), the factors of ‘delays’ and ‘waiting periods’ were identified as the as the key waste causing variables. Josephson and Saukkoriipi (2003) identified the hidden costs due to poor quality work and highlighted the factor of ‘injuries’ an important, but less significant cause for the non-physical waste generation.

This qualitative grade was then converted into a semi-quantitative number (*ci*) such as high=5, medium=3 and low=1. Finally, to attain the literature score (*LS*), frequency (*n*) of each factor was multiplied with its semi-quantitative contextual importance (*ci*). *LS* was then normalized for ranking as shown in Table 2.2.

3.2 Data collection

To develop an SD model, data was collected in two stages; stage one data was used for developing influence matrix, which was further used to establish causal loop diagram. While stage two data was used for developing a quantitative SD model to quantify the non-physical waste produced in a building project of two years. The detailed process is explained in the subsequent sections.

3.2.1 Stage one

To quantify the total amount of non-physical waste generated in a building project, it is necessary to understand the interrelationships between the causing factors (Josephson and Saukkoriipi, 2003). Therefore, a preliminary survey was conducted to develop an influence matrix. This short survey was based on three main questions; influence of a factor on the other factors, nature of influence i.e. directly or inversely proportional and the rate of influence on a Likert scale of 1-5, where 5=highest influence and 1=lowest influence. The questions were asked for all 16 factors in a one-way relationship. Further, self-influence of factors was not considered. In total, 120 relationships were formulated containing a total of 360 questions. The questionnaire was sent to over 30 experienced and specialized field professionals, out of which 18 responses were received and 16 found valid. The specialized nature of this data collection may allow representativeness based on this sample size (VanVoorhis and Morgan, 2007, Kotrlik and Higgins, 2001).

Afterward, an influence matrix based on the responses of survey was developed, which acts as the foundation for developing a CLD. Only those influencing relations were used to develop CLD where one factor acts as an immediate cause for the other factor. Such as design changes influence the waiting periods, delays, rework, etc., but under the given framework, only errors can cause a design change which further effects the decision process time.

3.2.2 Stage two

Han et al. (2011) used non-value adding activity generation patterns and timings of occurrence to classify factors. A similar classification method has been used in the current study. Identified factors were grouped into three main categories; interruptions occurring before execution of an activity, productivity loss during execution and rework caused after execution. The detailed categorization has been shown in Figure 3-2.

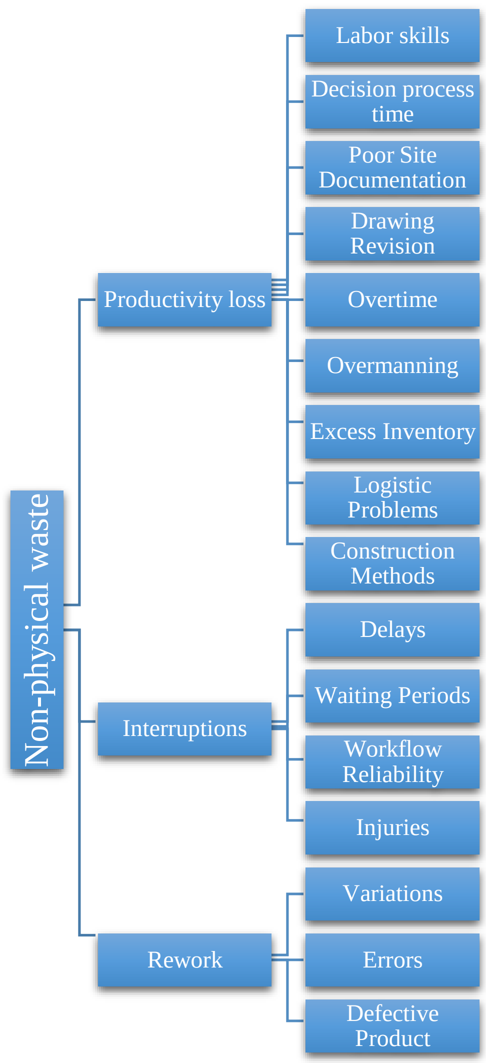

Figure 3-2: Categorization of identified factors

The three main groups of non-physical waste, i.e. productivity loss, interruption and rework, share a common feature. In each category, a certain amount of resources is wasted and additional resources are required to supplement the original schedule of work (Zhao and Chua, 2003). To mathematically formulate the amount of non-physical waste, a questionnaire was developed in Google® Forms consisting of two sections; the first section collected respondent information such as qualification, field of experience, job description, professional experience and country of origin. In the second section, respondents were asked about the impact of each category of non-value adding activity on the non-physical waste on a scale of 0 to 9, where 0=no impact and 9=highest impact. Further, respondents were asked about the impact of each identified factor on the non-value adding activity.

3.3 Model development

The CLD serves as the basis for developing a system dynamics model. The dynamic behavior of this model is determined by the feedback loops in the CLD (Yuan, 2011). The interactions of all variables show how the system is dynamically influenced. The CLD based on influence matrix is converted to a stock and flow diagram using VENSIM®. All three main group heads; productivity loss, interruptions and rework, together with the non-physical waste act as stocks governed by an inflow and outflow rate. The equations for rates were determined by using the data from influence matrix and stage two data collection.

Chapter 4

4 RESULTS AND DISCUSSION

4.1 Causal loop diagram

The preliminary survey conducted in stage one of data collection was used to develop an influence matrix. There were a total of 120 combinations as only unidirectional influences were considered. These combinations were presented to various senior field experts with average experience of 9 years. Out of 120 possible combinations, field experts confirmed 85 relationships with actual influence. The impact of each influence was solicited from the experts which was then averaged and normalized for input into the SD model. To develop CLD, the finalized 85 relationships were scrutinized for immediate causality. It is important to note that considering all influences rather than immediate causes among variables reflects the past behavior of a system and does not represent the structure of the system (Sterman, 2000). Thus, influences with no direct effect were dropped from further analysis and only those relationships were considered that capture the underlying causal structure of the system keeping the feedback loops closed and meaningful.

Table 4-1: Influence matrix for CLD

	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9	K_{10}	K_{11}	K_{12}	K_{13}	K_{14}	K_{15}	K_{16}
K_1	1.00						0.73					0.68				
K_2		1.00		0.83		0.45										
K_3			1.00				-0.57									
K_4				1.00					0.64		0.63				0.42	0.64
K_5					1.00		0.82									
K_6						1.00										
K_7							1.00			0.54						
K_8								1.00							0.51	
K_9									1.00							
K_{10}										1.00						
K_{11}											1.00					
K_{12}												1.00	0.63			
K_{13}													1.00			
K_{14}														1.00		
K_{15}															1.00	
K_{16}																1.00

K_1: Variations; K_2: Waiting Periods; K_3: Labor skills; K_4: Delays; K_5: Defective Product; K_6: Excess Inventory; K_7: Errors; K_8: Overmanning; K_9: Logistics; K_{10}: Processes; K_{11}: Workflow Reliability; K_{12}: Decision-making process; K_{13}: Poor site documentation; K_{14}: Overtime; K_{15}: Injuries; K_{16}: Slow drawing revision

As a result, the developed matrix given in Table 4-1 shows only causal relationships instead of all influencing relationships. Such as ‘excess inventory’ is usually influenced by ‘logistic problems’, ‘poor site documentation’, ‘workflow reliability’, ‘processes’, ‘delays’ and ‘decision making process’. However, under the developed framework, it only causes an increase in the waiting periods to acquire material from the storage, which further causes delays in the project. Hence, it only acts as an exogenous variable that effects the system but is not affected by the system. This influence matrix formed the basis for developing a qualitative CLD. The developed CLD in Figure 4-1 provides an in-depth understanding of the dynamics of interrelated factors causing non-physical waste in building projects.

The CLD illustrates four important reinforcing loops; R1, R2, R3 and R4. All factors used to develop the CLD are causing non-physical waste in building projects, therefore no balancing loop exists in the diagram. In the explanation of R1, it is usual to encounter errors during execution when dealing with a design and construction project. Construction processes and methods govern the amount of errors occurring in projects. Considering R1, if the construction methods employed are less adequate, there will be more errors in the project which will result into an increased number of variations and rework if errors occur during the design and execution phases respectively. More rework will cause an increase in the non-physical waste generation which leads to decreased productivity giving a rise in the schedule pressure as shown by negative polarity sign. To counter the increased schedule pressure, site managers often use overtime which can fatigue and jeopardize the labor skills, causing further errors.

The reinforcing loops R2 and R3 can be defined such as that an increased schedule pressure often pushes the managers to use extra resources in the form of overmanning, but with overmanning comes the conflict of time and space that leads to logistic problems, making labor more susceptible to accidents. Interruptions resulting from injuries and logistic issues result into delays, generating non-physical waste. Finally, reinforcing loop R4 implies that an increased number of variations due to errors results into an increased decision time by managers, which is further enhanced in the case of poor site documentation such as poor progress reports. This increase in decision time causes an increase in the time utilized by design team for drawing revisions and amendments. This results into interruptions before execution of activities and can be triggered by waiting periods resulting from excess inventory in the form of poor material management. These delays are one of the significant reasons for non-physical waste generation.

On the basis of these conditions and relations of CLD, the following section introduces a quantitative SD model that can systematically quantify the amount of non-physical waste.

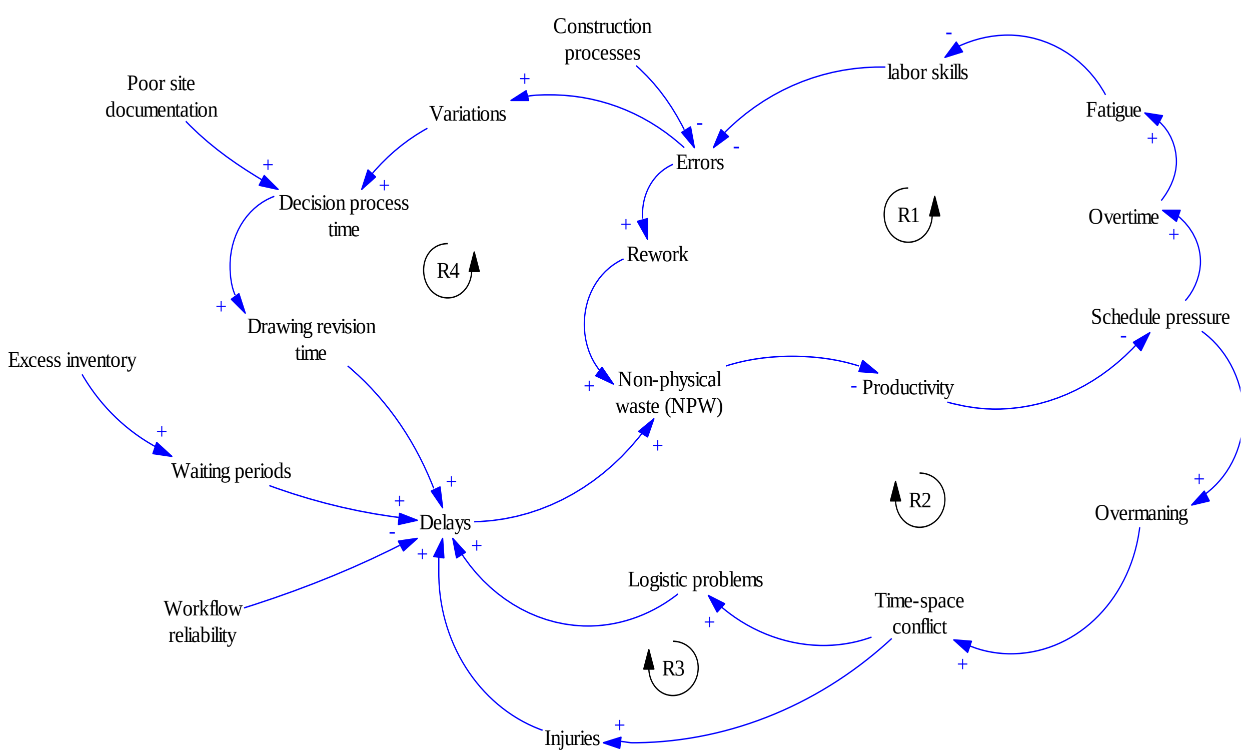

Figure 4-1: Feedback causal loop diagram

4.2 SD model

After developing CLD that describes the feedback mechanism, it was first converted to stock and flow diagram, and finally to an SD model shown in Figure 4-2. The model consists of four variables, excess inventory (K_6), processes (K_{10}), workflow reliability (K_{11}) and poor site documentation (K_{13}) acting as exogenous items and four stocks, 'interruptions', 'rework' and 'productivity loss' and 'non-physical waste' (NPW) governed by the flow rates. Interruptions, rework and productivity loss accumulate using 'waste generation rate' that ultimately generates NPW. The data collected in stage two was used to develop the equation for 'waste generation rate'. A total of 89 responses were collected with the demographic details given in Table 4-2.

Table 4-2: Demographic details of respondents

Respondent Demography		Frequency	Percentage
Qualification	Bachelors	46	52
	B. Tech	1	1
	Masters	40	45
	PhD	2	2
Organization Type	Government	17	19
	Semi-government	11	12
	Private	55	62
	International agencies	2	2
	NGOs	4	5
Field of experience	Traditional buildings	84	95
	Prefabricated buildings	5	5
Experience	0 - 5 Years	65	72
	5 - 10 Years	17	20
	10 -15 Years	2	2
	More than 15 Years	5	6
Country	Pakistan	65	73
	Qatar	6	7
	UAE	2	2
	USA	3	3
	Australia	4	5
	Saudi Arabia	3	3
	Others	6	7

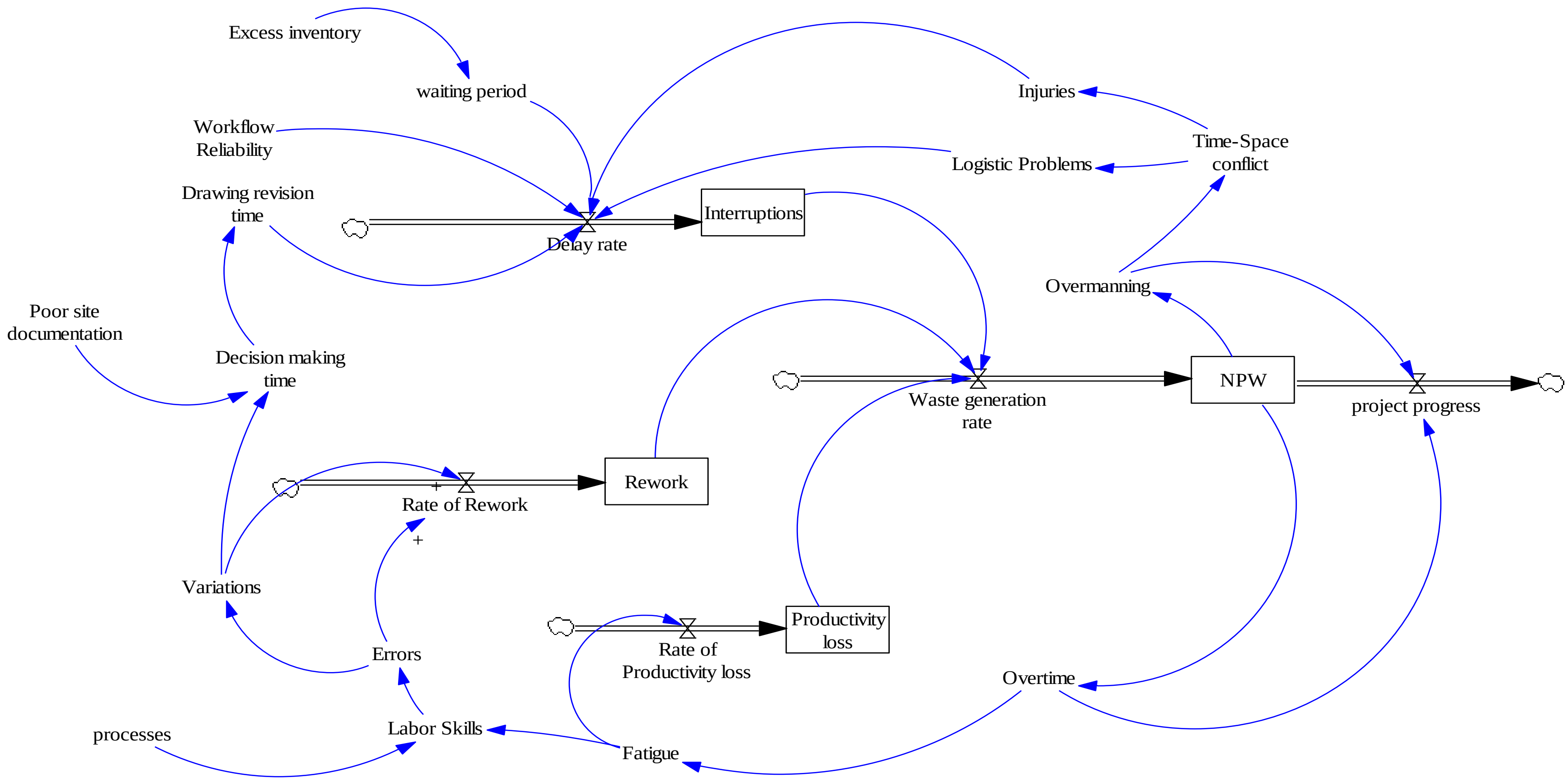

Figure 4-2: Quantitative SD model

To check the internal reliability of the data collected in the stage two, Cronbach's alpha test was performed. The value of statistic was $\alpha = 0.824$, which makes the data reliable as the calculated value is greater than 0.7 (Huang et al., 2012). Further, to develop an equation for waste generation rate, mode value was used instead of the average as it represents more than 25% of the data in each question. The impact score was then normalized and formulated in Equation 1, where ω_1= 'rework', ω_2= 'productivity loss' and ω_3= 'interruptions'.

$$waste\ genenation\ rate = 0.364\omega_1 + +0.318(\omega_2 + \omega_3) \qquad \text{Equation 1}$$

Similarly, functions for rates of delay, rework and productivity loss were established using normalized impact scores and causal relation scores from the developed influence matrix as mathematically given in Equations 2, 3 and 4.

$$Delay\ rate = 0.834 * K_2 + 0.64 * K_9 + 0.634 * K_{11} + 0.422 * K_{15} + 0.644 \qquad \text{Equation 2}$$

$$Rate\ of\ rewrok = 1.00 * K_1 + 0.889 * K_7 \qquad \text{Equation 3}$$

$$Rate\ of\ productivity\ loss = 0.56 * K_{17} \qquad \text{Equation 4}$$

Further, to mathematically link the interrelationships between the variables, the normalized influence score was used. An initial value of 20% was given to all four exogenous variables for the base simulation. In addition to those identified from literature, two extra variables, 'time-space conflict (K_{18})' and 'fatigue (K_{17})', were used for simplified structure and understanding of SD model.

4.3 Simulation results and discussion

The simulation represents the system's behavior over time which illustrates the generation of NPW over a 24-months building project. The graphical curve in Figure 4-3 shows an increasing function which implies that the inflow is greater than the outflow. The NPW is minimum at 0 months. However, it reaches to a maximum value of 21% in 24 months under the base run. This exponential curve is produced as a result of reinforcing loop that reflects the compounding effect of all interacting variables and also illustrates that with an increased amount of NPW, the project progress decreases (Zhao and Chua, 2003). In a similar study, Han et al. (2011) determined that 26% of total efforts are wasted considering only errors and design changes in a bridge project.

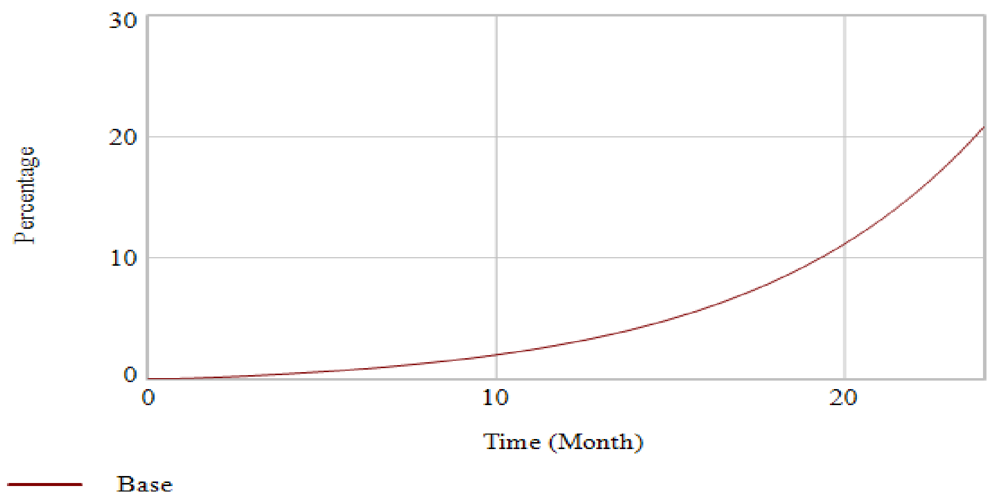

Figure 4-3: Base run for NPW generation

Further, simulations were run for four different scenarios; in scenario 1, as shown in Figure 4-4, the initial values for three exogenous variables were kept at 20% and value for excess inventory (K_6) was increased to 60% and 90% respectively. The waste generated increased from 21% in base run to a maximum 35%. This shows that although an excess inventory contributes to waste generation, its impact is less significant (Alwi et al., 2002b). JIT principle of lean construction can reduce waste produced in scenario 1 as it emphasizes on material management by avoiding unnecessary stocking (Ajayi et al., 2017).

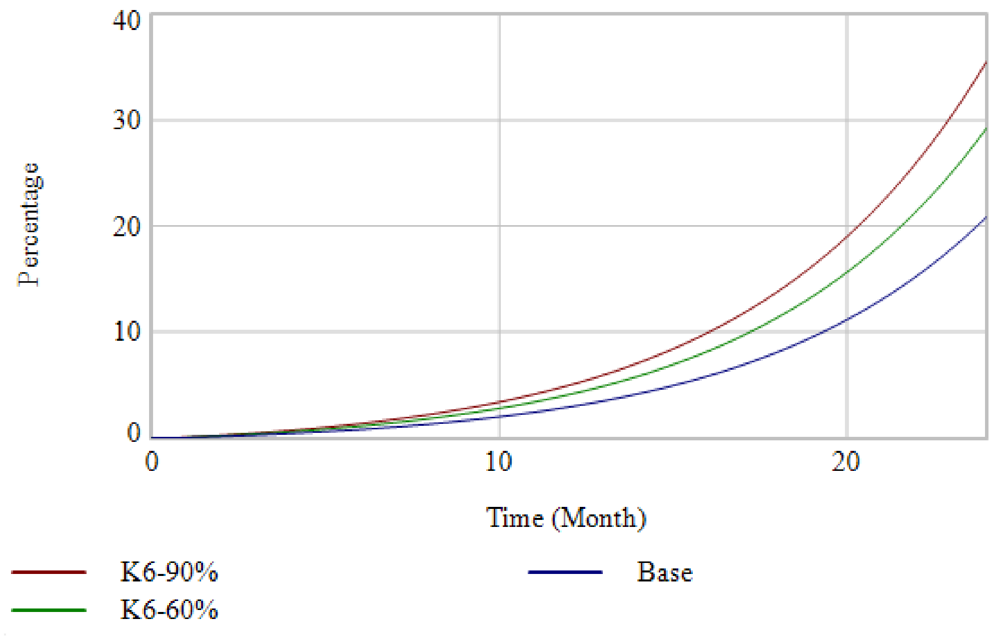

Figure 4-4: Scenario 1

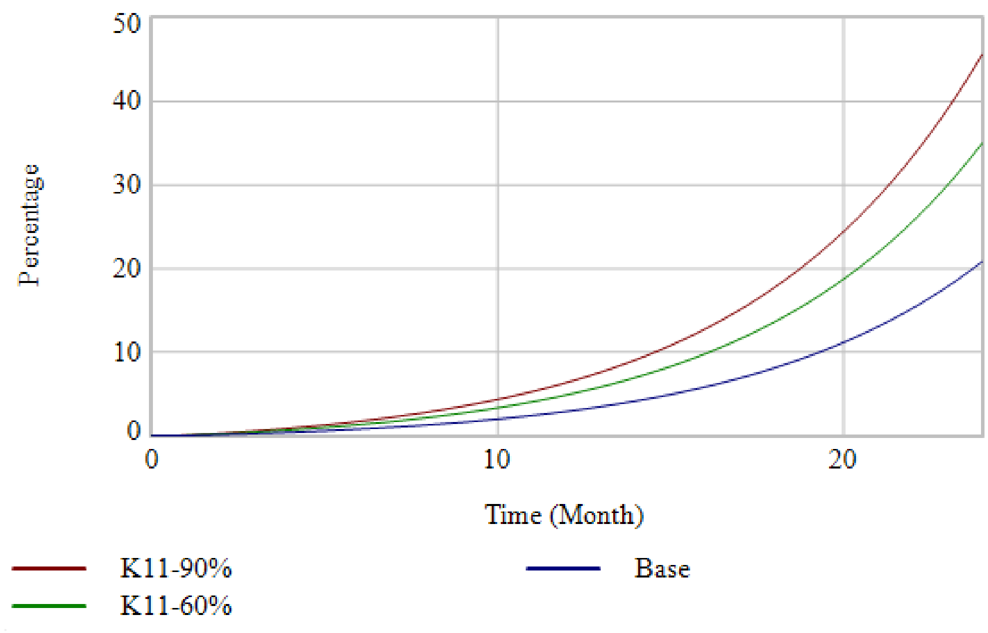

Figure 4-5: Scenario 2

Scenarios 2 and 3 shown in Figure 4-5 and Figure 4-6 respectively highlight that both workflow reliability (K_{11}) and processes (K_{10}) equally affect the NPW generation. The value for NPW in both scenarios rises to maximum 46% when 90% of workflow unreliability or inadequate construction processes exist in the project. In this context, the study by Khanh and Kim (2015) highlighted that workflow reliability and construction processes are of equal and significant cause for NPW generation. Lean construction helps in improving the workflow reliability and management by emphasizing on long term contractual relationships and can improve labor efficiency, reducing the waste in the form of time overruns (Thomas et al., 2003). Lean construction principles of relationship improvement, and fundamental changes in design and construction processes are important NPW control strategies (Green and May, 2005).

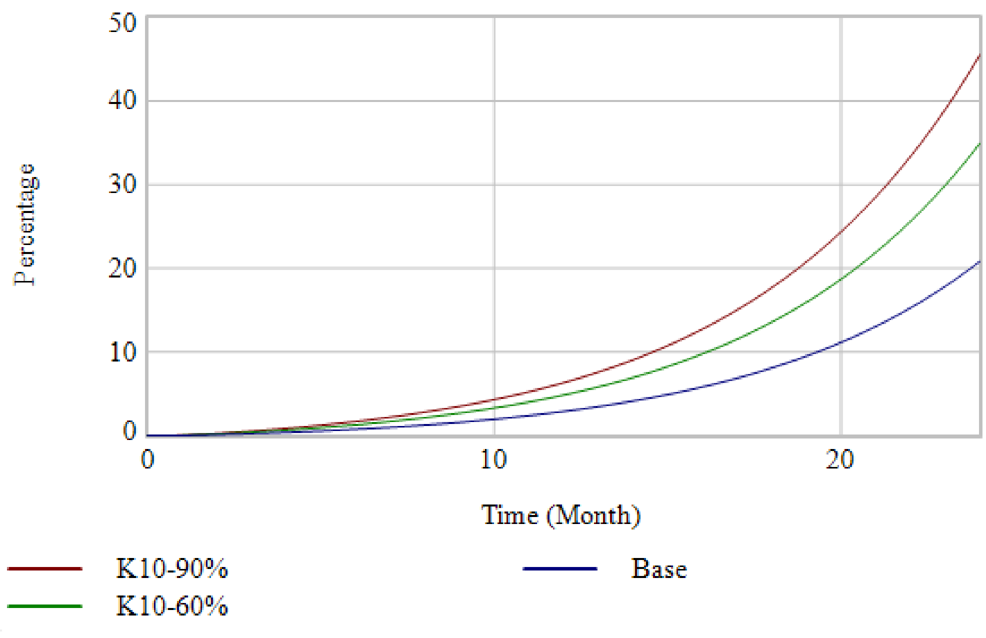

Figure 4-6: Scenario 3

Lastly, scenario 4 shown in Figure 4-7 explains that poor site documentation is of least significance amongst the four contributing exogenous variables, as the value for NPW increases to a maximum of 29% when 90% of site documentation is of poor quality. This is also reflected by the ranking shown in Table 2.2: Qualitative analysis of identified factors Table 2.2, where it has been ranked at 13th position amongst the 16 identified factors. A relatable study by Alwi et al. (2002a) ranked poor site documentation at 29th amongst 31 factors contributing to NPW generation and concluded it to have less significant impact on waste production.

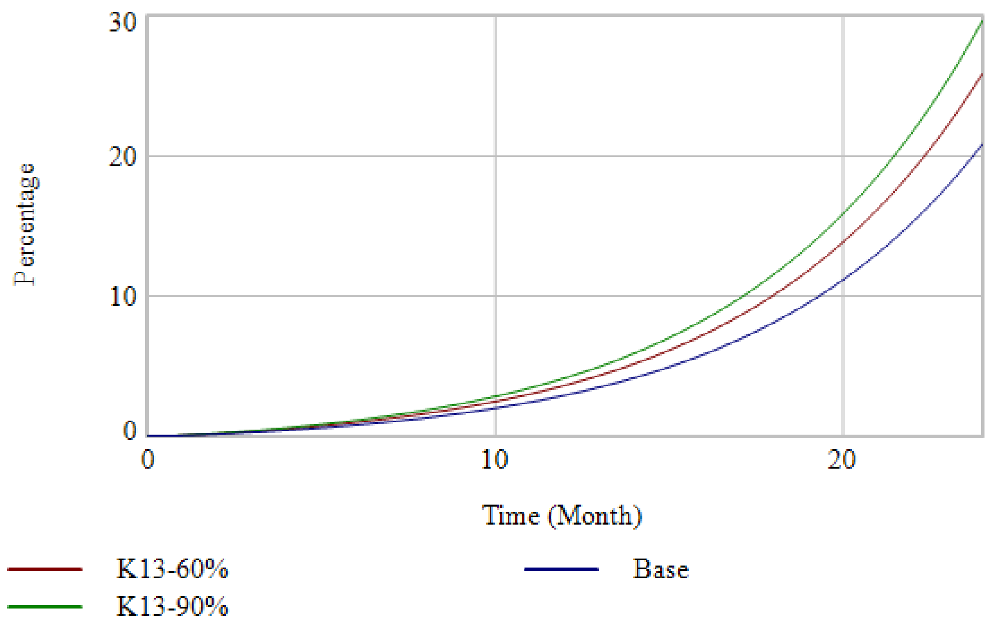

Figure 4-7: Scenario 4

4.4 Model validation

A system dynamics model addresses a specific problem, not a general, and the confidence that can be placed in the model to help analyze the given problem should not depend upon whether the model can address other problems (Richardson and Pugh III, 1981). In this regard, the model validity depends on the purpose for which the model is developed (Sterman, 2000). As described above, the crux of developed SD model is to quantify NPW generated in building projects as a result of non-value adding activities. Therefore, the validation of model structure is the first step of validating SD model. Qudrat-Ullah and Seong (2010) listed following tests that are used for structural validity of an SD model.

4.4.1 Boundary-adequacy test

Sterman (2000) explained three purposes of this test; whether all the important concepts in addressing the problem are endogenous to the model, if the behaviors of the model change significantly when boundary assumptions are relaxed and whether the policy recommendations change when the model boundary is extended. After examining all the variables in the SD model, it is found that each of these variables is essential, as all the variables have been identified from literature and causes NPW generation at both design and construction phases of building projects. Most of the NPW causing factors are endogenous such as variations, delays and errors, except for four of them which act as exogenous constants that contribute to NPW.

4.4.2 Structure verification test

This step of validation is of immense significance and the aim is to check whether the model structure is consistent with relevant descriptive knowledge used in the model. The developed CLD depends on variables identified from the literature and then field professionals provided with the influencing interrelations amongst all variables. Therefore, the model structure is logical and closely represents the actual system in the industry. This is in line with the methodology followed by Qudrat-Ullah and Seong (2010).

4.4.3 Parameter verification

The mathematical functions developed to link the variables are based on responses from field experts that ensure empirical and theoretical foundations. Further, the developed simulation scenarios confirm that the model exhibits results which are relatable to previous studies (Han et al., 2011).

4.4.4 Extreme condition test

The purpose of this test is to check if each equation makes sense when extreme values are used as input and if meaningful results are achieved at extreme condition without simulation failure or error (Sterman, 2000). Simulation scenarios developed in the above section explains that even when the values for constants are increased to 90%, still the results are meaningful and if all constants are given initial value of 100%, the amount of NPW produced is more than 100% with least amount of project progress as all efforts are wasted as a result of NPW, as shown in Figure 4-8.

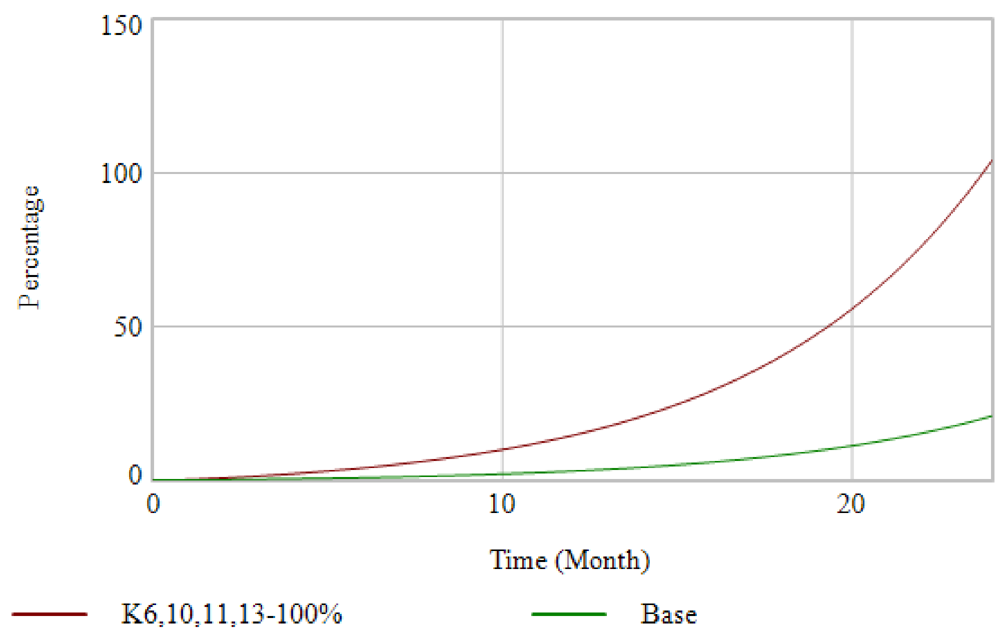

Figure 4-8: NPW generated at extreme value

4.4.5 Model behavior verification test

Apart from the four structural verification tests, the model behavior verification test is employed to compare the simulation results with actual data. Since under current construction practices, no project examines the amount of NPW generated so no real project data is available to verify the simulation results. However, Sargent (2000) suggests that a comparison with already validated similar model is a suitable technique to verify a simulation model. Therefore comparing the findings of current SD model to Han et al. (2011), where 26% of the efforts were wasted as a result of non-value adding activities and Figure 4-3 suggesting 21% of NPW generated as a compounding effect at 20% of poor site documentation, excess inventory, workflow unreliability and inadequate construction processes each, the current model stands valid to address the defined objectives of this study.

Chapter 5

5 CONCLUSIONS AND RECOMMENDATIONS

With an aim to economize the construction projects, the current research identified the significant factors that contribute to intangible waste in the form of non-value adding activities which were then used to quantify NPW in building projects. The novelty of study lies in the proposed SD model for quantifying the NPW using macro level factors such as rework, errors, variations, etc., and micro level factors like waiting periods, drawing revision time and poor site documentation. For this purpose, a two-stage data collection process was deployed where data from experts was collected in the first stage to develop an influence matrix that served as the foundation for designing CLD and then further converted to a quantitative stock and flow diagram in the second stage. Simulation results revealed that in the base run with exogenous factors of excess inventory (K_6), processes (K_{10}), workflow reliability (K_{11}) and poor site documentation (K_{13}) each with an initial value of 20%, a total of 21% NPW was generated in a 24-month period. The value for NPW increases for any increase in the value of exogenous constants; this increase is a result of the SD model with four reinforcing loops. Further, the sensitivity analysis performed using four scenarios depicted that poor site documentation (K_{13}) is of least significant impact. Lean construction tool of LPS is considered an effective and well-known planning and control system to mitigate management flaws of poor site documentation and reporting (Gao and Low, 2014). Processes (K_{10}) and workflow reliability (K_{11}) were observed to have equal and significant impact on NPW generation, highlighting the importance of lean theory which emphasizes on long term contracts with suppliers ensuring reliability and, new effective design and construction methods such as offsite construction (Hosseini et al., 2012, Nahmens and Ikuma, 2011).

Although the developed model serves best the objectives of the study to quantify NPW, no model is perfect and improvements can always be made (Ding et al., 2016). With this pretext, it is proposed such future research investigating the impact of NPW on project productivity that can help to develop more understanding for project managers. Moreover, including experts from offsite construction and developing a separate model for precast buildings will help in understanding NPW generation for traditional and offsite construction methods proposed by lean theory.

The developed SD model has important practical implications, such as restructuring manager's strategy of overmanning and overtime for controlling time and cost overrun, and developing an understanding of wasted efforts due to existence of non-value adding activities. The findings of this research also address the issue of the nonexistence of NPW quantification method in practice and literature.

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Appendices

Appendix I: Initial Survey

Non-physical construction waste quantification and optimization using lean construction principles

This research aims to quantify the non-physical waste as a result of non-value adding activities that consume resources but do not add value. 16 factors have been identified from literature that cause non-physical (immaterial) waste during construction. This questionnaire intends to understand the interrelationship between the factors.

Please contribute to this survey using your work experience if factor in column "i" influence factors in column "j" and if they do influence one another please select the appropriate relationship i.e., positive or negative and the value on a scale of 1 to 5. Your response to this survey is highly appreciated.

Field of Experience:	☐Traditional Building Projects ☐ Prefabricated Building Projects
Organization	
Years of Experience:	
Country:	
Email Address:	

S. NO	Factors	Description
1	Design Changes/Variations	Design Changes & Errors during project execution
2	Waiting Periods (instructions, material & equipment)	Time utilized as waiting for instructions, material and equipment acquisition
3	Labor skills	Poor labor skills causing productivity loss
4	Delays	Delays due to internal and external factors on site
5	Defective Product (rework)	Rework caused as a result of defective product
6	Inventory	Excess inventory and material storage problems due to limited space and resources
7	Errors	Errors in design or drawings
8	Overmanning	Problems associated with over allocation of labor for increasing productivity
9	Logistics (unnecessary movement of labor & equipment)	Unnecessary movement of labor and equipment
10	Processes	Improper construction processes causing wastage
11	Workflow Reliability	Unavailability of labor and material due to poor supplier or planning
12	Decision making process	Slow decision making processes before and during execution of project
13	Poor site documentation	Poor record keeping of activities on site/Poor progress reports
14	Overtime	Overtime of labor for increasing productivity resulting in poor quality work
15	Injuries	Accidents and injuries due to poor trainings and construction processes
16	Slow drawing revision	Time consuming revisions by design team

			CRITERIA	Factor (i) influence Factor (j)?					How much?
i	j	Factor(i)		Factor(j)	YES	NO	+	-	1 to 5
1	2	Design Changes/Variations		Waiting Periods (instructions, material & equipment)					
1	3			Labor skills					
1	4			Delays					
1	5			Defective Product (rework)					
1	6			Inventory					
1	7			Errors					
1	8			Overmanning					
1	9			Logistics (unnecessary movement of labor & equipment)					
1	10			Processes					
1	11			Workflow Reliability					
1	12			Decision making process					
1	13			Poor site documentation					
1	14			Overtime					
1	15			Injuries					
1	16			Slow drawing revision					
2	3	Waiting Periods (instructions, material & equipment)		Labor skills					
2	4			Delays					
2	5			Defective Product (rework)					
2	6			Inventory					
2	7			Errors					
2	8			Overmanning					
2	9			Logistics (unnecessary movement of labor & equipment)					
2	10			Processes					
2	11			Workflow Reliability					
2	12			Decision making process					
2	13			Poor site documentation					
2	14			Overtime					
2	15			Injuries					
2	16			Slow drawing revision					
3	4	Labor skills		Delays					
3	5			Defective Product (rework)					
3	6			Inventory					
3	7			Errors					
3	8			Overmaning					
3	9			Logistics (unnecessary movement of labor & equipment)					
3	10			Processes					
3	11			Workflow Reliability					
3	12			Decision making process					
3	13			Poor site documentation					
3	14			Overtime					
3	15			Injuries					
3	16			Slow drawing revision					
4	5	Delays		Defective Product (rework)					
4	6			Inventory					
4	7			Errors					
4	8			Overmaning					
4	9			Logistics (unnecessary movement of labor & equipment)					
4	10			Processes					
4	11			Workflow Reliability					

4	12			Decision making process					
4	13			Poor site documentation					
4	14			Overtime					
4	15			Injuries					
4	16			Slow drawing revision					
5	6	Defective Product (rework)		Inventory					
5	7			Errors					
5	8			Overmanning					
5	9			Logistics (unnecessary movement of labor & equipment)					
5	10			Processes					
5	11			Workflow Reliability					
5	12			Decision making process					
5	13			Poor site documentation					
5	14			Overtime					
5	15			Injuries					
5	16			Slow drawing revision					
6	7			Errors					
6	8	Inventory		Overmanning					
6	9			Logistics (unnecessary movement of labor & equipment)					
6	10			Processes					
6	11			Workflow Reliability					
6	12			Decision making process					
6	13			Poor site documentation					
6	14			Overtime					
6	15			Injuries					
6	16			Slow drawing revision					
7	8			Overmanning					
7	9	Errors		Logistics (unnecessary movement of labor & equipment)					
7	10			Processes					
7	11			Workflow Reliability					
7	12			Decision making process					
7	13			Poor site documentation					
7	14			Overtime					
7	15			Injuries					
7	16			Slow drawing revision					
8	9			Logistics (unnecessary movement of labor & equipment)					
8	10	Overmanning		Processes					
8	11			Workflow Reliability					
8	12			Decision making process					
8	13			Poor site documentation					
8	14			Overtime					
8	15			Injuries					
8	16			Slow drawing revision					
9	10	Logistics (unnecessary movement of labor & equipment)		Processes					
9	11			Workflow Reliability					
9	12			Decision making process					
9	13			Poor site documentation					
9	14			Overtime					
9	15			Injuries					
9	16			Slow drawing revision					
10	11	Processes		Workflow Reliability					
10	12			Decision making process					
10	13			Poor site documentation					
10	14			Overtime					

10	15			Injuries					
10	16			Slow drawing revision					
11	12	Workflow Reliability		Decision making process					
11	13			Poor site documentation					
11	14			Overtime					
11	15			Injuries					
11	16			Slow drawing revision					
12	13	Decision making process		Poor site documentation					
12	14			Overtime					
12	15			Injuries					
12	16			Slow drawing revision					
13	14	Poor site documentation		Overtime					
13	15			Injuries					
13	16			Slow drawing revision					
14	15	Overtime		Injuries					
14	16			Slow drawing revision					
15	16	Injuries		Slow drawing revision					

Appendix II: Google Form Questionnaire

Non-physical construction waste quantification and optimization using lean construction principles

Dear Sir/Madam,
This research aims to quantify the non-physical (immaterial) waste as a result of non-value adding activities that consume resources but do not add value to the construction project. Please contribute to the survey by selecting an impact score on a scale of 0 to 9, where 0 represents no impact and 9 represents the highest impact.

In case you have any questions, please feel free to contact me.
Regards,
Shahzaib Ahad Khan
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*Required

Personal Information

1. **Qualification:** *
Mark only one oval.

- ⬭ B.Tech
- ⬭ B.Sc/B.engg
- ⬭ M.Sc/M.Eng/M.Tech/P.G.Dip
- ⬭ PhD/D.Eng

2. **Field of experience:** *
Mark only one oval.

- ⬭ Traditional building projects
- ⬭ Prefabricated building projects

3. **Job title:** *
Mark only one oval.

- ( ) CEO
- ( ) Project Director
- ( ) Project Manager
- ( ) Construction Manager
- ( ) Assistant Manager
- ( ) Contract Administrator
- ( ) Project Engineer
- ( ) Planning Engineer
- ( ) Site Manager
- ( ) Architect/Designer
- ( ) Consultant
- ( ) University Teacher/Professor
- ( ) Other: ____________________

4. **Years of experience:** *
Mark only one oval.

- ( ) 0 to 5 Years
- ( ) 5 to 10 Years
- ( ) 10 to 15 Years
- ( ) More than 15 Years

5. **Organisation type:** *
Mark only one oval.

- ( ) Government
- ( ) Semi-Government
- ( ) Private
- ( ) International Funding Agencies
- ( ) NGOs
- ( ) University (Academia)
- ( ) Other: ____________________

6. **Country of work experience:** *

____

7. **Email address:**

____

Survey Questions

A total of 16 factors have been identified from literature that contributes to non-physical waste in construction. The 16 factors have been grouped under three categories, 1.Productivity, 2.Interruptions, 3.Rework.

8. **How much impact does "Productivity" has on the non-physical waste generation in construction?** *

Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

9. **How much impact does "Labor Skill" has on the productivity loss?** *

Expertise of labor.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

10. **How much impact does "Decision Making Process" has on the productivity loss?** *

Time utilized by management for decisions.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

11. **How much impact does "Poor Site Documentation" has on the productivity loss?** *

Improper progress reports.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

12. **How much impact does "Slow Drawing Revision" has on the productivity loss?** *

Slow revision processes causing delays.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

13. **How much impact does "Overtime" has on the productivity loss?** *

Workers and labor overtime for speeding up the work.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

14. **How much impact does "Overmanning" has on the productivity loss?** *
Overmanning is excess labor employed to complete activities which are not on schedule
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

15. **How much impact does "Excess Inventory" has on the productivity loss?** *
Excess inventory problems due to limited space and resources for material handling.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

16. **How much impact does "Unnecessary Movement of Labor and Equipment" has on the productivity loss?** *
Logistic problems during execution of work.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

17. **How much impact does "Construction Methods"have on the productivity loss?** *
Different construction methods employed e.g: manual excavation, using concrete pumps etc
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

18. **How much impact does "Work Interruptions" have on non-physical waste generation?** *
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

19. **How much impact does "Delays" has on interruption?** *
Delays due to external or internal factors.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

20. **How much impact does "Waiting Periods" has on interruption? ***

Waiting time for acquiring tools and material on site.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

21. **How much impact does "Workflow Reliability" has on interruption? ***

"workflow reliability": timely availability of material/equipment/labor by supplier
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

22. **How much impact does "Injuries" has on interruption? ***

Accidents and injuries occurring on site.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

23. **How much impact does "Rework" has on non-physical waste generation? ***

Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

24. **How much impact does "Design Changes and variations" have on rework? ***

Change orders during execution of work.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

25. **How much impact does "Design Errors" have on rework? ***

Errors in design drawings and specifications.
Mark only one oval.

0	1	2	3	4	5	6	7	8	9
⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

26. **How much impact does "Defective Product" has on rework?** *

Poor quality product

Mark only one oval.

0	1	2	3	4	5	6	7	8	9
◯	◯	◯	◯	◯	◯	◯	◯	◯	◯

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