IMPROVING CONSTRUCTION PROCESSES BY INTEGRATING LEAN, GREEN, AND SIX-SIGMA

by

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Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2013

UNIVERSITY OF PITTSBURGH

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The overall goal of this research was to develop and implement methods to improve the performance and the efficiency of construction processes prior to and during the construction phase in Design-Bid-Build (DBB) projects. In order to accomplish these goals, the three methods Lean, Green, and Six-Sigma were implemented in two different scenarios and validated by case studies.

First, a framework was developed that integrated the three methods - Lean, Green, and Six-Sigma with an overall layout of the Define, Measure, Analyze, Improve, and Control (DMAIC) improvement model. The framework was then validated through the construction process of installation of pile caps for an educational institute during the construction phase in Pittsburgh. The framework highlighted two issues with the pile caps construction process. First, disparate quantities of materials (purchased and installed) were determined. Second, the pile caps construction process took a total time of 54 business days while it could have been completed in 30 business days. Using life cycle assessment, environmental impacts of the pile cap construction process were analyzed and results showed that major environmental impacts including global warming potential, release of carcinogenics, negative respiratory effects, ozone depletion, and ecotoxcity could result from the materials used for the process. Next, the root causes behind waste generation were determined via developing and administrating a questionnaire to a local construction company.

Second, the previously developed framework was further validated and applied to a residential development project in Saudi Arabia. The construction sector has been growing rapidly in Saudi Arabia; however, the quality of Saudi Arabian construction is decreasing, resulting in excess waste generation and associated environmental impacts. This case study examined a project with 53 residential units overall but only 10 units acceptable at final inspection. The largest quality issue was determined to be exterior paint blistering. Using the developed framework, defective units were investigated through a field examination, narrowing down the causes of the blistering applying the Pareto method as follows: Inadequate method, untrained workers, weather, and others. Next, the Process improvement tool was applied to reduce the blistering causes and to improve the current process. A new method was designed and applied to a separate residential unit for validation. The modified method showed a great improvement and in the end the unit was able to pass inspection.

Finally, building on the previous case studies, the framework was later refined with the goal of applying it earlier in a project, prior to construction, to further reduce potential waste generation and associated environmental impacts. Using Lean Green, and Six-Sigma (LG6) and adopting the same improvement model, DMAIC, the owner can evaluate all steps separately in the process, addressing all resources consumed and analyzing environmental impacts which might be generated; this highlights potential waste and so can help the owner avoid waste occurrence by indicating where the process needs to be amended to create less environmental impact and more efficiency. For this research, the model was used to help evaluate the construction process for the installation of 160 woodpiles. The model identified that four steps out of eight were considered as non-adding value steps or waste. Three steps out of four non-adding value steps were involved with mobilization and demobilization of the equipment. The remaining wasteful step was cutting to length all installed woodpiles. The model showed that if these steps were replaced, eliminated or planned well, environmental impacts would be reduced by 9%.

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NOMENCLATURE

A/E	Architecture Engineering firm
ACT.	Actual
C&D	Construction and Demolition
CT	Cycle Time
DBB	Design – Bid – Build
DB	Design – Build
DMAIC	Define, Measure, Analyze, Improve, Control
DOE	Design of Experiments
DPMO	Defect Per Million Opportunities
Eq	Equivalent
EST.	Estimated
FMEA	Failure Mode and Effects Analysis
GDP	Gross Domestic Product
GW	Global Warming
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design

NOMENCLATURE (CONT'D)

LG6	Lean, Green, Six-Sigma
MO	Modified Process
MSA	Measurement System Analysis
MCSI	Mascaro Centre for Sustainable Innovation
MYAS	Madinat Yanbu Al Sinaiyah
NVA/T	Non Value Added Time
OP	Original Process
PM	Particulate Matter
QCI	Quality, Cost, and Impacts
RCIY	Royal Commission for Industrial Yanbu
RP	Rejected Process
TIP	Total Industry Productivity
TQM	Total Quality Management
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
US	United States
USGBC	U. S. Green Building Council
USLCI	US Life Cycle Inventory

NOMENCLATURE (CONT'D)

VSM	Value Stream Mapping
WIP	Work In Process
VA/T	Value Added Time

PREFACE

I am extremely thankful for the help of my dissertation advisor, Dr. Melissa M. Bilec, who has been with me throughout these years as mentor, colleague, editor, and friend. Also I extend special thanks to my dissertation committee for their useful suggestions and guidance throughout my work.

I would to thank my colleagues and friends for their help and endless support during my study.

Finally, I owe my greatest debt to my family. I thank my parents for life and strength and the determination to live fully. Warm thanks to my kids Lana and Yazn, whom remind me daily that miracles exist everywhere around us. Most of all, I thank my beloved wife, Heba, who shares my burdens and my joys.

To all

Thank You.

1.0 INTRODUCTION

The construction industry contributed over $639 billion to the United States' Gross Domestic Product (GDP) in 2009 (U.S. Department of Commerce 2010). Moreover, the U.S. has over nine million workers employed in the construction industry (U.S. Census Bureau 2010). In Saudi Arabia, the construction sector represented 6.4% of the total country's GDP in 2010 (Saudi National Commercial Bnak 2011). In Qatar, the total investment in the construction sector is forecasted to be USD 225 million in total by the end of 2020 (The Commercial Bank of Qatar Q.S.C. 2012). As the construction industry produces an abundance of waste and consumes vast quantities of resources and energy, this increase in construction is troubling. In Saudi Arabia, for example, the demand for cement reached about 36.7 million tons, one third of US cement consumption in 2008 (Saudi National Commercial Bnak 2011; Portland Cement Association 2012). In the United States, 136 million tons of the solid waste entering landfills, constituting roughly one-third of all the solid waste, is from the construction sector (U.S. Environmental Protection Agency 2003). In addition, money, time, and resources are also wasted as a result of inefficient or poorly managed construction projects. Improving the efficiency and management of construction projects, then, can result in savings related to resources, energy, and cost.

While previous construction related studies have focused on the reduction of waste, increase of productivity, or minimization of environmental impacts, to date, limited research has been done to combine all three efforts. This research integrates three methods: lean to reduce waste, green to lower the environmental impact, and Six-Sigma to improve quality and productivity, in the belief that all three methods together could help minimize all of the above-mentioned impacts generated by construction activities.

1.1 WHY LEAN, GREEN, AND SIX-SIGMA?

The three methods Lean, Green, and Six-Sigma are complementary; therefore, use of all three would allow more comprehensive analysis of waste and impacts. Lean is valued for its ability to identify waste in the process. For example, Lean does not quantify environmental consequences; therefore, for this research, the aim was to consider ‘greening’ via life cycle assessment to fill this gap and evaluate the environmental impacts of the generated waste. However, while together, Lean and green have the ability to identify waste and evaluate environmental impact, they often do not suggest an actual method to reduce waste. Six-Sigma has the potential to fill this gap.

1.2 RESEARCH GOALS AND OBJECTIVES

The overall goals of this research are to develop and find ways to improve the environmental performance and to enhance the efficiency of the construction processes during and prior to the construction phase. To accomplish these goals, this research applied three methods: Lean, Green, and Six-Sigma, in a systematic approach following the five phase improvement model: Define, Measure, Analyze, Improve, Control (DMAIC). The specific objectives were:

1) To develop a systematic framework intended for use in the construction phase that integrates Lean, Green, and Six-Sigma methods in order to improve the environmental performance of the construction process during the construction phase.
2) To validate the framework by implementing it during the construction phase during a project in the Kingdom of Saudi Arabia.
3) To create a quality model applying a form of DMAIC that integrates Lean, Green, and Six-Sigma (LG6) intended for pre-construction phases that can help contractors plan and implement construction projects in an efficient manner. This involves using the developed LG6 model to identify potential sources of waste early in the process, i.e., prior to the construction phase.

The research objectives were developed to be implemented on Design-Bid-Build type of projects, where the contractor is not involved in the design phase (see Figure 1).

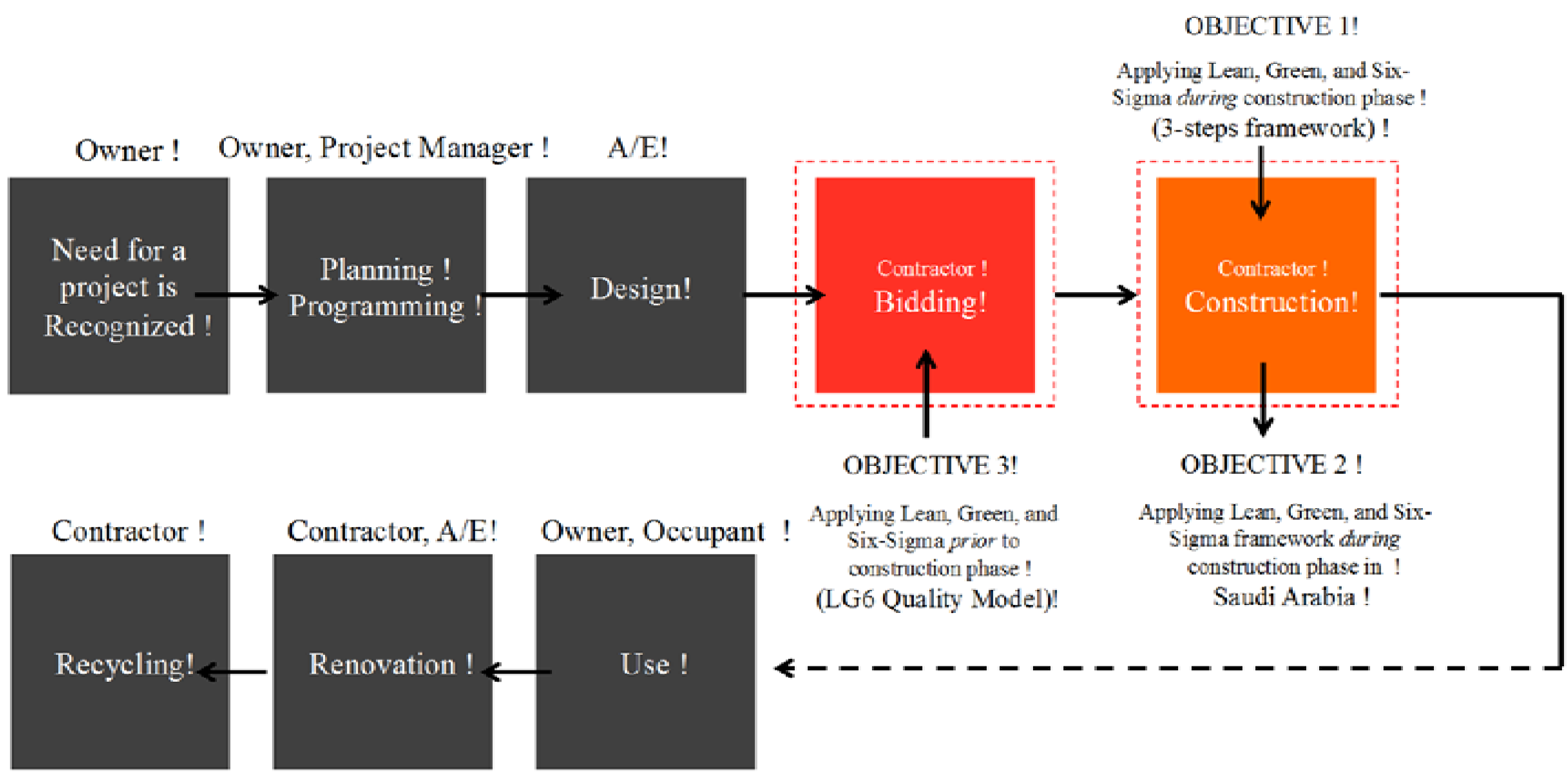


Figure 1 Project Phases in Design-Bid- Build Contract and Research Objectives 1, 2, and 3

1.3 INTELLECTUAL MERIT

This study has beneficial intellectual merit for several reasons: it will provide a better understanding of how construction activities can have negative environmental impacts if not planned well. This research will increase the awareness of identifying waste in construction processes so that it can be prevented or eliminated. The study's findings will encourage contractors to establish new construction methods or choose materials that are environmentally friendly. The methods developed here could help contractors who seek to have their projects LEED certified. For instance, the LG6 quality model helps contractors devise different options to be implemented including; equipment with lower emissions, materials with lower impacts and methods with less acquisition of resources. The investigator of this research study has the proper knowledge and experience to execute these tasks.

Currently, there is no study that has combined all three methods, Lean, Green, and Six-Sigma to develop improvement tool that would help enhance the environmental performance of the construction processes during or prior to construction phase. The novelty in the work is combing these methods into a common system and using this system in an untapped sector.

1.4 BROADER IMPACT

This study has a broader impact on the community for several reasons. First, it teaches college students novel methods to improve the quality of any type of job processes. Second, it involves collaboration between the educational sector and the construction industry – a sector that contributed substantially to U.S. GDP and is among major consumers of natural resources, as reported by the U.S. Environmental Protection Agency in 2009. Also, this research helps to enhance the knowledge of construction workers by introducing them to several concepts such as waste definition, types, environmental consequences, and importance of quality. In addition, this research encourages the environmental impacts to be included in change orders. Enabled by the findings of this research, both parties can cooperate for ideal practice; projects to be completed with the optimal use of natural resources with minimal environmental impact.

2.0 BACKGROUND AND LITERATURE REVIEW

The nature of the construction industry is complex. Construction projects need to be expertly managed in terms of considering not only budgets and schedules, but also quality and environmental impacts (Howell and Ballard 1998; Formoso, Soibelman et al. 2002). Lean, Green, and Six-Sigma are different methods that are already often used independently to address quality, waste, and environmental impacts in construction.

Previous studies have addressed improving the quality of construction processes and strategies for the reduction of construction waste (Bossink and Brouwers 1996; Chase 1998; Ekanayake and Ofori 2000; Love, Edwards et al. 2009). For example, Serpell and Alarcun (1998) created a framework for improving construction processes through use of a set of structured activities and tools to help increase quality. Wang (2008) created an automated quality management system that helps gather, filter, manage, monitor and share quality data between different crews participating in a construction project. This system was able to enhance information flow to produce cost savings and to increase the speed of completion of the project while at the same time improving the quality of the product.

Arditi and Gunaydin (1997) addressed the importance of process quality to construction companies. One way to improve process quality is through Total Quality Management (TQM), which has shown great benefits when applied in manufacturing industries. The successful implementation of TQM in the construction industry requires a commitment to quality from both management and workers. In addition, the implementation of technological advances in design and construction and full knowledge of the assembly process amongst workers have been identified as factors influencing Total Industry Productivity (TIP) for construction (Ganesan 1984). The impact of effective pre-construction planning on the reduction of waste was highlighted in a survey of high rise construction projects in Hong Kong which showed that execution of work orders with incomplete contract documentation can result in the loss of quality in several areas such as frequent variation in design, inaccurate material orders, as well as delivery scheduling difficulties (Poon, Yu et al. 2004).

2.1 LEAN DEFINES WASTE IN PROCESS

Lean is a business strategy with the primary objective of eliminating waste, with waste being defined as "anything that does not add value." In Lean, the customer defines value. Value-added activities are ones that the customer is willing to pay for, the ones that help transform the product or service in some way, and the ones that must be done correctly the first time. Taiiachi Ohno, the father of the Toyota Production System, identified seven different forms of waste (Ohno 1990), including:

1) Transport: Moving products or materials around is waste; because the more things are moved the more chance there is for damage to occur.

2) Waiting: Waiting is any form is waste.

3) Overproduction: Producing more than what the customer needs is waste. Overproduction causes unnecessary inventory cost, materials consumption, and manpower.

4) Defect: Any process that fails to transfer inputs to desired outputs is considered waste. Any failure to meet the customer's requirements is considered waste.

5) Inventory: Any inventory is considered a non-value added commodity, even though it may be needed. Once inventoried, it is at risk of damage, obsolescence, spoilage, and quality issues.

6) Motion: Any physical movement by people that does not add value to the process is waste, including moving things, walking, lifting, etc.

7) Extra Processing: Any processing that does not add value to the product is waste.

2.1.1 Value Stream Map (VSM)

The Lean method offers various tools to help identify any of the seven types of waste in process mentioned above. A well-known and commonly used Lean tool is Value Stream Mapping (VSM), a technique that creates a process flow diagram of materials and information. VSM uses a systematic approach, covering all activities required to bring the product or service to completion, and shows all the steps, highlighting any ineffectiveness in the value stream. The following key elements are important in VSM (Sayer and Williams 2007):

Process steps*:* VSM depicts each of the process steps in the value stream, including both value-added and non-value-added. The VSM reveals process statistics, including cycle time, number of operators, quantity of inventory, and number of pieces.

Inventory*:* VSM highlights the storage as well the quantity and movement of inventory within the process.

Information flow: VSM depicts all supporting information required by the process, including schedules, specifications, and orders.

Cycle Time (CT): CT includes the time required to complete one cycle of the operation, or one step in the process.

Work in process (WIP): WIP includes the condition of all products that are neither raw materials nor final products.

2.1.2 Applying Lean to Construction

Using Lean strategies, Garrett and Lee (2011) analyze the submission and review processes of a typical construction project and concluded that incomplete or deficient documentation raised problems during construction; once Lean tools were applied to reduce non-value added activates, measureable reduction in both process and lead times was achieved. Lapinski, Horman et al. (2006) examined Toyota's successful implementation of Lean methodologies to minimize costs in construction, specifically how Lean can reduce the high initial expense of green building projects by eliminating process waste. Specifically at the process level, Pasqualini and Zawislak (2005) applied Value Stream Mapping (VSM) to masonry construction to highlight all associated waste sources, including extra inventories and delays; however, they did not identify the causes of proposed solutions. Another study using Lean by Yu, Tweed et al. (2009) found that poorly managed production flows resulted in significant construction waste; they then used VSM to analyze and restructure the system to minimize waste.

In Lean, identifying the value stream is the how value will be realized and establishes when and how decisions should be made. Mapping the value stream shows when the information necessary to meet the owner's requirements will be available and when it will be required.

This research used VSM since it can be used to explain an entire system with the goal of developing a comprehensive Lean system (Howell and Ballard 1998). Some researchers have paired VSM and construction, with efforts focused on the macro process level, such as supply chains (Arbulu and Tommelein 2002; Fontanini and Picchi 2004), project delivery (Yu, Tweed et al. 2009), or a single construction process such as fabricating masonry (Pasqualini and Zawislak 2005) or component manufacturing (Da CL Alves, Tommelein et al. 2005).

However, this research also demonstrates that while VSM has the ability to outline processes, simplifying the identification of waste, VSM does not have the ability to analyze the environmental impact to help improve a construction process prior to or during the construction phase.

2.2 GREEN REDUCES ENVIRONMENTAL IMPACT

Although Lean has the potential to identify the waste in the process, Lean does not quantify the environmental impacts of waste in the construction process. Therefore, in this research, Life Cycle Assessment (LCA) was used in conjunction with Lean to allow evaluation of the environmental impact of construction process prior to and during the construction phase.

Massive construction activities are under way globally in an effort to meet the projected demands of a rapidly growing world population. Building in the United States annually consumes 66% of the total produced electricity and 40% of the total primary energy generated (U.S.Energy Information Adminstartion 2010). As a result, many initiatives have been established to improve the environmental performance of the built environment. The process of applying such initiatives can be labeled "greening." Greening is the collective term for a variety of principles and approaches aimed at minimizing or eliminating the environmental impact of a product or activity. For instance, the U.S. Green Building Council (USGBC) has developed a rating system named Leadership in Energy and Environmental Design (LEED) that rates; the success of the LEED rating system is evident in the more that 13,400 certified buildings in the United States (U.S. Green Building Council USGBC 2009).

2.2.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a green tool that that systematically assesses and manages the environmental impact of a product, process, or service through its entire life cycle, from the material and energy used in the raw material extraction and production processes, through acquisition and product use, and continuing to final product disposal. The International Standardization Organization (ISO) has formalized LCA into a four-step process (International Organization for Standardization 2006):

1) Goal and scope definition: goals and objectives, boundaries, and functional units are identified and established.

2) Life Cycle Inventory (LCI): data inventory are collected from different sources such as relevant literature and databases. Inventories are collected according to the system boundaries; these include all necessary inventories required in order to achieve to defined goal. This an important phase since the LCA's final results will depend on the quality of the LCI.

3) Life Cycle Impact Assessment (LCIA): during this step, LCI data is converted into an understandable and quantifiable environmental impact, for example, Global Warming Potential (GWP). The LCIA tool used in this research is the Tool for Reduction and Assessment of Chemical and other environmental Impacts (TRACI), developed by the U.S. Environmental Protection Agency. TRACI translates the environmental loads identified by the LCI into nine different categories. These categories include ozone depletion, global warming, acidification,

eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria-related effects, human health cancer effects, human health non-cancer effects, fossil fuel depletion, and land use effects. Each impact is calculated on a midpoint basis and is presented in kg Equivalent of a reference substance (U.S. Environmental Protection Agency 2010).

4) Interpretation: during this step, recommendations are made to improve environmental performance and aid project managers in decision-making with respect to the final product and process results.

2.2.2 Life Cycle Assessment addresses the environmental impact of on-site construction activities

With respect to *greening*, Life Cycle Assessment (LCA) has been used in previous studies to quantify the environmental impacts of construction. A life-cycle study developed by Bilec, Ries et al. (2006), for example, found that the construction phase, though not as significantly as the use phase, may have serious impacts on the environment, highlighting the generation of Particulate Matter (PM) emissions during construction phase. Guggemos and Horvath (2005) utilized LCA to examine strategies for reducing environmental impact of on-site construction activities, particularly the strategy of minimizing and reusing temporary materials during construction. They found that using well maintained or new construction equipment would improve the environmental impact of the construction phase. Aimed at better informing decision-makers seeking to add environmental quality and sustainable development to project goals, a study by Sharrard, Matthews et al. (2008) developed an input-output LCA estimating the comprehensive environmental effects of construction processes. A study by Li, Zhu et al. (2010) applied process LCA to work breakdown structures to help decision makers have a clearer understanding of the environmental impact of the material and equipment brought to the project during the construction phase.

While the previous studies illustrated how construction activities overall contributed to the life cycle environmental impacts of buildings, this research focused on evaluating the environmental impact of a single construction process.

2.3 SIX-SIGMA HELPS IMPROVE PROCESS PERFORMANCE

Although the Lean method is used to identify waste, it does not eliminate or reduce variability in processes. Six-Sigma, however, can improve processes by eliminating all types of root causes through a variety of tools.

Six-Sigma is a comprehensive method used to help businesses achieve and sustain a healthy level of success. The Six-Sigma system focuses on customer needs, statistical analyses, continuous improvement, and business reinvention. Sigma refers to the amount of inconstancy or variance occurring in a process, and Six-Sigma equates to 3.4 Defects Per Million Opportunities (DPMO). Most defect opportunity measures are translated into the DPMO format, which indicates how many defects, would arise if there were one million opportunities.

DPMO = (No. Of X (Defects) in the data collection sheet / No. Of opportunities of defects × No. Of Units) × 1,000,000 **Equation (2.1)**

Six-Sigma was introduced by Motorola and General Electric (GE) in the 1980s as a new set of management tools to help both companies. At that time, Motorola was searching for a solution to improve production inefficiencies; meanwhile, GE was trying to return to its former status after a significant decline. The status of the companies changed after the application of the Six-Sigma method to their businesses. Motorola accumulated savings from 1987 to 1997 totaling $14 billion, and by the end of 1998, GE had accumulated $750 million in sales, which grew to $1.5 billion by the end of 1999. Since the late 1990s many more companies have adopted Six-Sigma as part of their management strategy, including Honeywell, ASEA Brown Boveri, Black & Decker, Bombardier, Dupont, Dow Chemical, Federal Express, Johnson & Johnson, Kodak, Navistar, Polaroid, Sony, Toshiba, and many others (Pande, Neuman et al. 2000).

The Six-Sigma method has many benefits. Specifically, it 1) helps to identify and eliminate sources of variation in the process, 2) sustains success, 3) sets performance goals for all involved parties, 4) enhances value to customers, and 5) allows businesses to execute strategic change.

Define, Measure, Analyze, Improve, Control (DMAIC) is a five-step Six-Sigma improvement model. DMAIC is commonly used by Six-Sigma firms to improve the current capabilities of an existing process. A number of tools and methods can be used in each step of the DMAIC model. The DMAIC's five phases along with examples of the tools applied in each phase are presented in Table 1.

Table 1 Examples of tools and methods used in Define, Measure, Analyze, Improve, and Control

DMAIC Steps	Examples of tools or methods
Define: Identify the problem and the issues causing decreased customer satisfaction.	• Five whys and how. • System thinking. • Flowchart.
Measure: Collect data from the process.	• Measurement system analysis (MSA). • Benchmark.
Analyze: Evaluate the current process; identify the root causes of the problem.	• Cause & Effect Diagram. • Continual improvement. • Experiment.
Improve: Act on the data to change the process for improvement.	• Pareto Chart. • Design of Experiments (DOE). • Failure Mode and Effects Analysis (FMEA). • Process improvement. • Variation reduction.
Control: Monitor the process to sustain the gains	• Management commitment. • Control Plan. • Process behavior chart.

This research uses different Six-Sigma tools for the two different case studies. These tools are Cause and Effect Diagram, Pareto Chart, and Process improvement. The Cause and Effect Diagram and Pareto Chart will be used for the Chapter 3 case study and the Cause and Effect Diagram and Process Improvement tools will be used for the Chapter 4 case study.

2.3.1 Cause and Effect Diagram

The Cause and Effect Diagram, also known as "Fishbone" or "Ishikawa Diagram," is a categorical brainstorming graphic tool used for determining the root-cause hypothesis and the potential causes (the bones of the fish) of a specific effect (the head of the fish) (Munro, Maio et al. 2008). Cause and Effect Diagrams can help teams to focus on the problem itself and not on the history of the problem. Also, Cause and Effect Diagrams can aid in focusing the team members on the roots of the problem and not prescriptive symptoms.

2.3.2 Pareto Chart

The Pareto principle based on Vilfredo Pareto's research is an application of the 80/20 rule (Munro, Maio et al. 2008). Basically, the Pareto principle is that for any issue, the greatest impact is made by a few vital causes (20 percent) while a lesser impact is made by the many trivial causes (80 percent). A Pareto Chart arranges attribute data so that columns are arranged in descending order, with highest occurrences first, while using a cumulative line to track the percentage of each category/bar, which distinguishes the 20 percent of items that causes are the main causes of the problem. In other words, the Pareto chart focuses on those causes that will have the greatest impact if solved.

2.3.3 Process Improvement

The Process Improvement method is the act of making the system work better to meet customer needs. It is a vital element of implementing continual improvement. The purpose here is to look at overall variability and not only on the variation. The three elements, which cause variability in a process, include: instability, variation, and being off-target. Considering variation, instability, and being off-target at the time of developing the new process would help create a process with sustainable desired performance. Sustainable performance is a vital element in continual improvement (Munro, Maio et al. 2008).

To date, few papers have been published that discuss the application of integrating Six-sigma into construction (Pheng and Hui 2004; Stewart and Spencer 2006; Han, Chae et al. 2008).

2.4 APPLYING SIX-SIGMA TO CONSTRUCTION

With respect to quality of construction, Six-Sigma is a quantitative methodology that can establish definitive improvement goals to reduce process variability in current construction operations. Six-Sigma was combined with Lean in the Han, Chae et al. (2008) study and had a great effect on improving the performance of the original process. Six-Sigma evaluates the quality of an ongoing operation and quantifies the goals of improvement for targeted workflow so as to control the critical sources of variability. Pheng and Hui (2004) applied Defects Per Million Opportunities (DPMO) as the Six-Sigma process-performance metric to internal finishing processes for a residential construction project. The low process performance—2 sigma—encouraged the contractor to supervise its on-going building projects more closely, better ensuring that the level of workmanship for the internal finishes complied with overall quality standards. Stewart and Spencer (2006) used DMAIC as a model to help enhance interactions between project teams, reduce project delays and provide a structured process-improvement strategy, ultimately improving the productivity of the beam construction process for a railway station. DMAIC offers a solid procedure for gathering information, and enabling process quality improvement.

Overall, although a fairly robust body of literature exists with detailed information on these three methods individually, there is a gap in research and practice with respect to combining Lean, Green, and Six-Sigma into one framework for comprehensive improvement of the construction processes (see Figure 2).

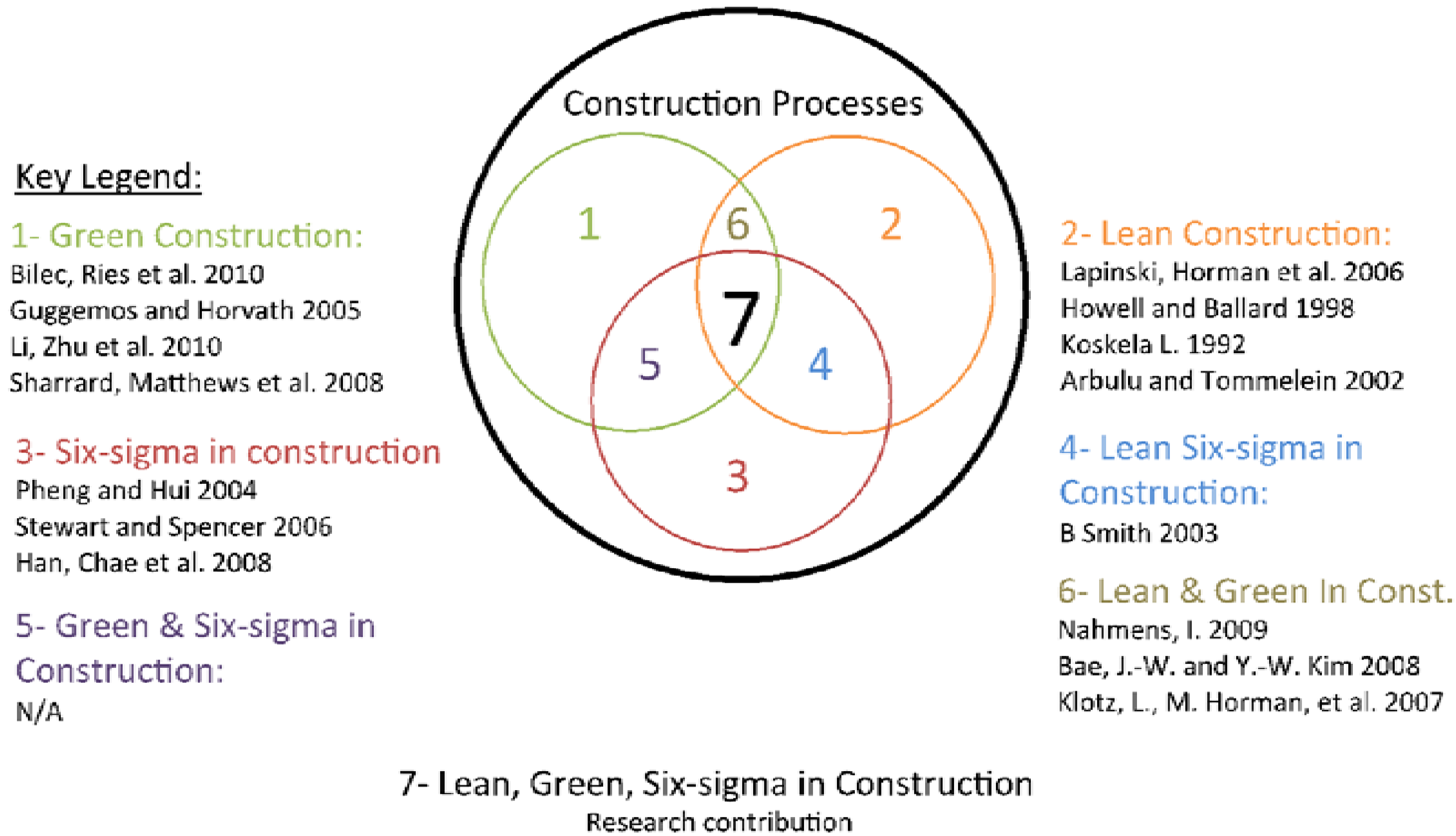


Figure 2 Literature review and research contribution

2.5 OUTLINE OF DISSERTATION

Chapter 3 addresses Objective 1, which is to develop a systematic framework that integrates Lean, Green, and Six-Sigma methods in order to improve the environmental performance of the construction process *during the construction phase*, using DMAIC steps. This work has been submitted to the *International Journal of Construction Management* and is currently under review.

Chapter 4 addresses Objective 2, where the developed Lean, Green, and Six-Sigma framework from Objective 1 was applied to evaluate and improve construction processes in the Kingdom of Saudi Arabia. This work has been submitted to the *Journal of Construction Engineering and Project Management*.

Chapter 5 addresses Objective 3, creating a quality model by applying a form of DMAIC that integrates Lean, Green, and Six-Sigma called (LG6) in order to help contractors plan and implement construction projects in an efficient manner. Putting the developed LG6 model into practice can help to identify potential sources of waste early in the process, prior to the construction phase.

3.0 A FRAMEWORK TO IMPROVE CONSTRUCTION PROCESSES: INTEGRATING LEAN, GREEN, AND SIX-SIGMA

The following chapter is an article under review in the *International Journal of Construction Management* with the citation:

Banawi, A., M. Bilec, "A Framework to Improve Construction Processes: Integrating Lean, Green and Six-Sigma." International Journal of Construction Management, 2013: Under review.

Supporting Information submitted with the work to the *International Journal of Construction Management* appears in Appendix B.

3.1 ABSTRACT

The construction industry consumes a significant amount of resources annually, generates significant waste, and produces a host of emissions. This work develops a framework and integrates three different approaches—Lean, Green, and Six-Sigma—in a systematic approach with the goal of improving the quality and environmental impacts of the construction process. A case study of pile cap installation is conducted to illustrate the application of the framework and associated results. The study highlights two issues within the pile cap construction process responsible for waste: delay and potential errors in material estimation and ordering. It describes the environmental impacts arising from waste and analyzes the root causes behind waste generation to enable improved process performance. A survey of field professionals regarding the causal factors of waste in everyday construction activities identified "Design changes during construction" as responsible for 48% of waste occurrences during construction, confirm results from the literature. In conclusion, the Lean Green Six-Sigma framework offers a comprehensive, multi-stage approach for process improvement minimization of life cycle environmental impacts.

3.2 INTRODUCTION

The construction industry contributed over $639 billion to the United States' Gross Domestic Product (GDP) in 2009 (U.S. Department of Commerce 2010); moreover, it employs over nine million workers (U.S. Census Bureau 2010). At the same time, the construction industry consumes vast quantities of resources and energy and produces an abundance of waste. In the U.S. in 2002, 136 million tons, constituting roughly one-third of the solid waste entering landfills, was from construction activities alone (U.S. Environmental Protection Agency 2003). Resources, energy, and cost are wasted as a result of inefficient or poorly managed construction projects. Therefore, improving the efficiency and management of construction projects can result in savings related to these assets. While previous construction-related studies have focused on how to reduce waste (Pasqualini and Zawislak 2005), minimize environmental impacts (Bilec, Ries et al. 2006; Bilec, Ries et al. 2010), or increase productivity (Pheng and Hui 2004), to date, limited research has been done examining how to achieve all three in combination. This research integrates three methods - Lean to reduce waste, Green to assess the environmental impact, and Six-Sigma to improve productivity - in an attempt to do so. The hypothesis is that use of all three methods together will help minimize impacts generated by construction activities while also improving efficiency and safeguarding the bottom line.

The main goal of this study is to develop a framework that incorporates all three methods, Lean, LCA, and Six-Sigma, to quantify and reduce the waste associated with construction. To achieve this goal, several objectives were completed:

1) Identifying waste at different stages in the construction process via the Lean tool VSM.
2) Quantifying the environmental impacts of resulting waste via LCA.

3) Eliminating or reducing the sources of waste via Six-sigma tools.

3.3 FRAMEWORK

The overall framework structure is based on Six-sigma's DMAIC. The designed DMAIC framework consists of three steps, described below and illustrated in Figure 3.

Step 1: Define and Measure - After selecting a construction process for evaluation, concurrently apply both Lean (VSM) and Green (LCA) methodologies to determine if waste is generated in the process and then quantify the environmental impacts of the waste.

Step 2: Analyze and Improve - If the process generates waste, then select and apply one or more appropriate Six-sigma tools to eliminate or reduce waste. Essentially the framework contains Six-sigma tools "nested" within Step 2. For example, Figure 1 shows the Cause and Effect Diagram and the Pareto chart as the chosen Six-sigma tools; however any Six-sigma tool(s) could be executed for use in Step 2 based on the case needs.

Step 3: Control - Re-evaluate using Lean (VSM) and Green (LCA) to determine the extent of waste reduction.

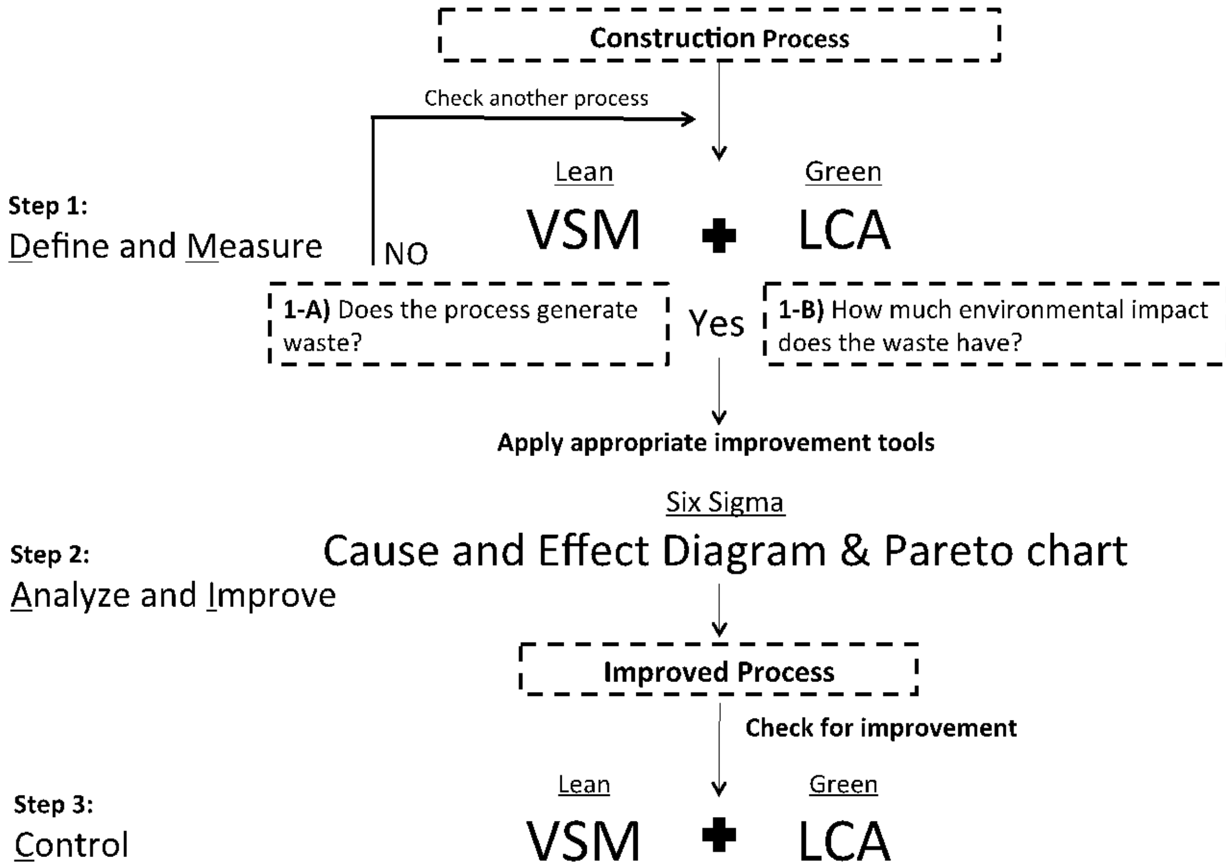


Figure 3 Lean, Green, Six-Sigma framework

3.4 METHOD

3.4.1 Case Study

A case study was done to illustrate the functionality of the framework. The case study "test" was deliberately simple to truly test the framework. The construction process used was the installation of pile caps for the Mascaro Center for Sustainable Innovations (MCSI) building, a

42,000 sq. ft. green building adjacent and integral to the Swanson School of Engineering at the University of Pittsburgh. The project cost $16 million and took 19 months to complete, from January 2008 to August 2009.

The pile cap construction process consisted of: 1) cutting the top of piles, 2) excavating for the pile cap installation, 3) forming the pile caps, and 4) placing and finishing the concrete. The pile cap process was deemed ideal for this study because it is a common construction activity typically having a common construction waste, specifically, concrete and formworks (U.S. Environmental Protection Agency 2003).

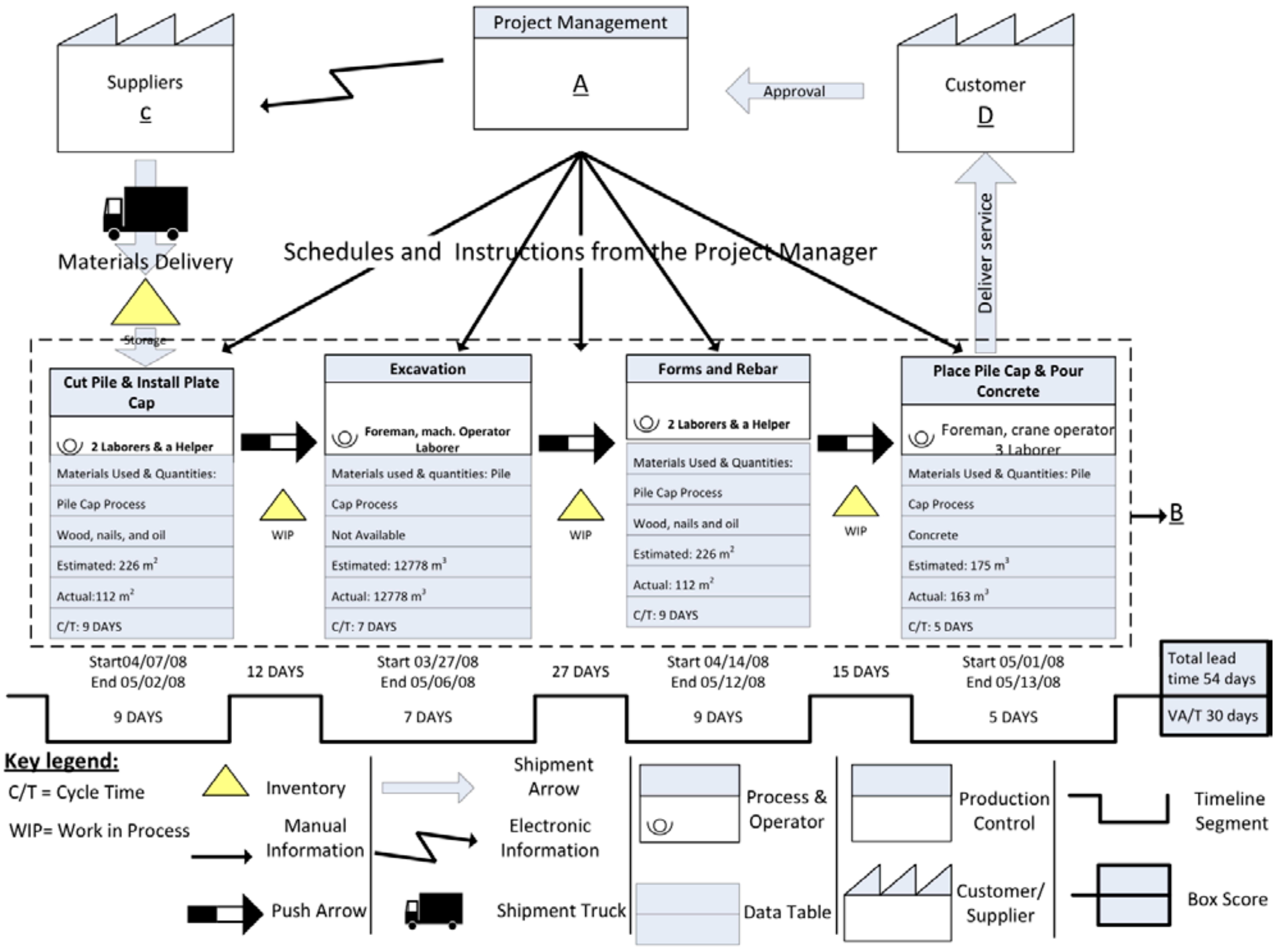


Figure 4 Value Stream Mapping (VSM) of the pile caps process.

Note: VSM is step 1-A from Figure 1

3.5 RESULTS AND DISCUSSION

In Step 1-A, a Value Stream Map (VSM) was developed in order to identify, for each step of the pile cap process, where waste may occur (Figure 4). A VSM systematically illustrates the relationships between the actors, data flows, and logistics. For this study, the VSM organized the four major elements: A) project management, B) installation of the pile cap process, C) supplier, and D) customer. One notable feature of the VSM is the data table, which can be used to organize process-related data, such as time, money, and materials used. In this case study, the information recorded in the data table includes crew composition and size, materials type, estimated material, installed materials, and cycle time. Cycle time (C/T) and delay time are illustrated on the timeline.

For step 1-B, Green, LCA was used to evaluate the environmental impacts of the pile cap process. The LCA system boundaries for the pile cap process includes raw materials extraction and manufacturing, transportation of equipment and materials to the site, waste disposal, and equipment usage on-site. LCA was used to evaluate both the actual and the estimated quantities of the materials, as well as to analyze the environmental impacts of changes in anticipated activity duration due to delays from 31 days to 54 days. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2 V3.01) (U.S. Environmental Protection Agency 2010) was then used to perform a life cycle impact assessment (LCIA).

The life cycle inventory data used to determine aggregate construction emissions for the pile cap process is shown in Table 2.

Table 2 Life cycle inventory, data sources and remarks for the pile cap process

Construction Related Activity			Remarks	Data Sources	References
Transportation	**Ton-Kilometer**				
	Estimated	**Actual**			
Operation, lorry >24t, EURO3/RER S	2380	2380	Included processes: Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre.	Ecoinvent system process	(SCLCI 1997)
Concrete, truck 32t,t	3642	3642	Included processes: Fuel consumption is included. Direct airborne emissions of gaseous substances, particulate matters and heavy metals are accounted for. Particulate emissions comprise exhaust- and abrasions emissions. Heavy metal emissions to soil and water caused by tyre.	Ecoinvent system process	(SCLCI 1997)
Equipment	**Fuel usage**				
	Estimated	**Actual**			
Excavation, hydraulic digger/ RER S	280 gal	280 gal	Included processes: Includes the inputs "hydraulic digger" for infrastructure, lubricating oil and fuel consumption, and some measured air emissions as output.	Ecoinvent system process	(SCLCI 1997)
Concrete pump, Diesel equipment 406HP	648 gal	648 gal	Included processes: Data for the cradle-to-gate resource requirements and emissions for the combustion of 1000 gallons of diesel fuel in industrial equipment. Average USA technology, late 1990's.	Franklin USA 98	(Sylvatica 2004)
Concrete Vibrator, Gasoline equipment 1.6 HP	10 gal	4 gal	Included processes: Data for the cradle-to-gate resource requirements and emissions for the combustion of 1000 gallons of gasoline in industrial equipment. Average USA technology, late 1990's.	Franklin USA 98	(Sylvatica 2004)
Concrete Saw, Gasoline equipment 5.6 HP	72 gal	19 gal	Included processes: Data for the cradle-to-gate resource requirements and emissions for the combustion of 1000 gallons of gasoline in industrial equipment. Average USA technology, late 1990's.	Franklin USA 98	(Sylvatica 2004)
Materials	**Material usage**				
	Estimated	**Actual**			
Concrete, sole plate and foundation, at plant/CH S	175m^3	163 m^3	Included processes: includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (transport, etc.) and infrastructure. No administration is included. Special outputs: wastewater, average data of 11 German concrete plants	Ecoinvent system process	Project's estimates documents
Plywood, at plywood plant, US PNW/kg/US	2428 sf	1200 sf	Included processes: final trim and saw to length of plywood. Base process data presented with allocations to within process co-products noted. Refer to allocation worksheet for specifics. All allocations performed using mass or volume.	USLCI	Project's estimates documents
Waste	**Quantities**				
Landfill/CH S			This record should only be used with Ecoinvent data	Ecoinvent system process	(SCLCI 1997)
Concrete, sole plate and foundation, at plant/CH S	12 cy		Included processes: includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (transport, etc.) and infrastructure. No administration is included. Special outputs: wastewater, average data of 11 German concrete plants	ecoinvent system processes	(SCLCI 1997)
Plywood, at plywood plant, US PNW/kg/US	600 sf		Included processes: final trim and saw to length of plywood. Base process data presented with allocations to within process co-products noted. Refer to allocation worksheet for specifics. All allocations performed using mass or volume.	ecoinvent system processes	(SCLCI 1997)

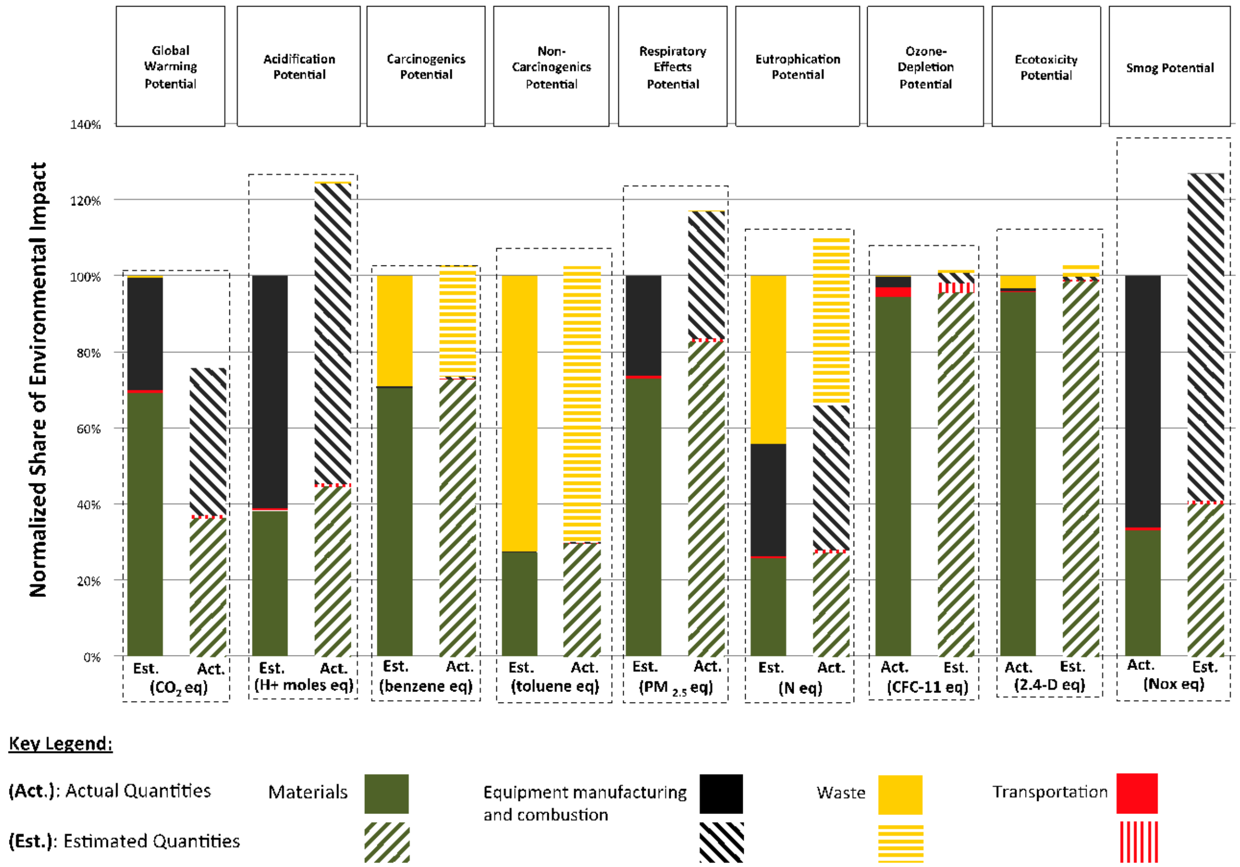


Figure 5 Life cycle environmental impacts of the pile cap process using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI).

The side-by-side comparison of the LCA results of the pile cap process for nine environmental impact categories is shown in Figure 5 for each of four process phases: Materials, Equipment manufacturing and combustion, Waste, and Transportation. Impact values were calculated based on both actual material use and times as well as estimated materials and time according to final contractor reports. Of the general environmental impacts, material use exhibited the highest share of impact in five of the nine categories. Environmental burdens in the other four categories arose in two cases from equipment manufacturing and combustion and in two categories of waste. Transportation showed the least environmental impact.

Materials accounted for the highest impacts in global warming potential, carcinogenics, respiratory effects, ozone depletion, and ecotoxicity. Cement manufacturing was a significant contributor to environmental impact from the material phase.

Equipment manufacturing and combustion contributed the highest environmental impacts in two categories: acidification and smog potential. Moreover, equipment contributed the highest after materials in terms of global warming potential and respiratory effects. Diesel combustion was a notable contributor to respiratory effects (Particulate Matter, $PM_{2.5}$), that is, effects leading to issues with the respiratory system, including asthma and lung cancer (U.S. Environmental Protection Agency 2010).

Although the quantity of material waste generated in comparison to the actual materials utilized was insignificant, the environmental impacts were able to be quantified. Waste generation and associated disposal had the highest environmental impact in the categories of non-carcinogenic potential and eutrophication potential. While the concrete delivery was the highest of the transportation processes, totaling 3642 ton–kilometers (see Table 2), transportation generated the lowest environmental impacts.

For step 2, Analyze & Improve, the Six-sigma process improvement method was implemented, with a Cause and Effect Diagram being used to analyze the root causes of the generated waste (Figure 6). Then a Pareto chart was used to explore how to improve the most commonly occurring waste causes. First, the Cause and Effect Diagram helped to identify the root causes of waste under several categories: Uncontrollable events, Materials, Labor, Machines, Methods, and Measure. Out of the 30 possible factors considered as possible causes of waste, only 16 are included on the Cause and Effect Diagram. These 16 were chosen based on two criteria: (1) the variables had to be independent, and (2) the factors had to have been researched extensively in the literature (Bossink and Brouwers 1996; Formoso, Soibelman et al. 2002; Poon, Yu et al. 2004). Independence here means that the occurrence of one cause of error does not affect the possibility that another of the 16 causes will occur. For example, having inexperienced workers could lead to errors by laborers, making it a dependent variable; on the other hand, damage during transportation could not lead to having materials which do not comply with specifications.

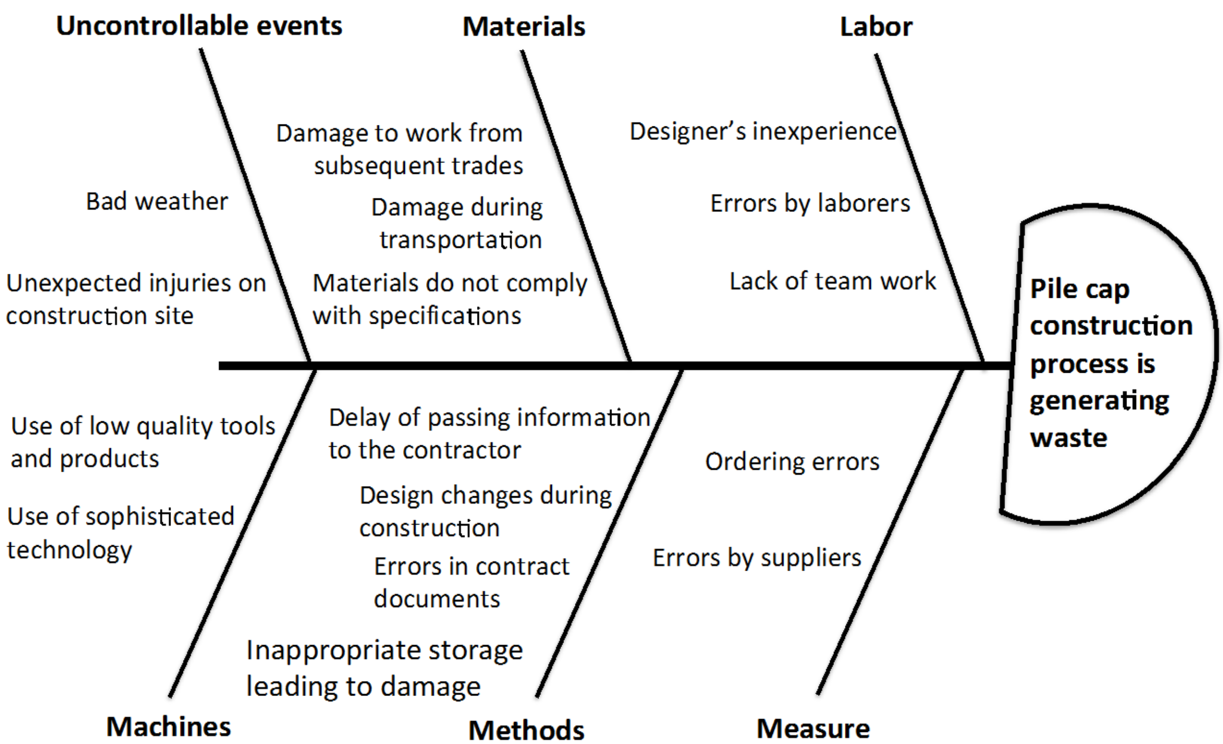


Figure 6 Cause and Effect Diagram: Common factors causing waste in the pile cap process

The set of 16 potential causal factors was further narrowed down via a two-step process to identify which factors contribute most to waste generation: First, a questionnaire was developed and sent to a construction claims consultant, who then distributed it to 30 employees involved with daily on-site construction claim activities. All 30 responses were returned within three days. In the questionnaire employees in the firm were asked to rank the 16 causal factors in order of importance, with number one being the highest, that is, most likely to generate waste. More data, including a description of the phases of questionnaire development, questionnaire sample and a table summarizing questionnaire results, can be found in Appendix B.

The Pareto chart was then used to create a representation of the feedback revealed by the questionnaire results. Applying the Pareto principles, each causal factor was given points based on how it was ranked in the employee questionnaire (Pande, Neuman et al. 2000). To elaborate more, if a factor rated first place it was assigned 12 points; second place, 6 points; third place, 3 points; and any place after third, 1 point. "Design changes during construction" ranked first overall, representing 46% of the total number of points. "Delay in passing information" ranked second representing 28%, and "Errors by laborers" was third place, representing 18% of the total. The remaining factors represented only 8% (Figure 7).

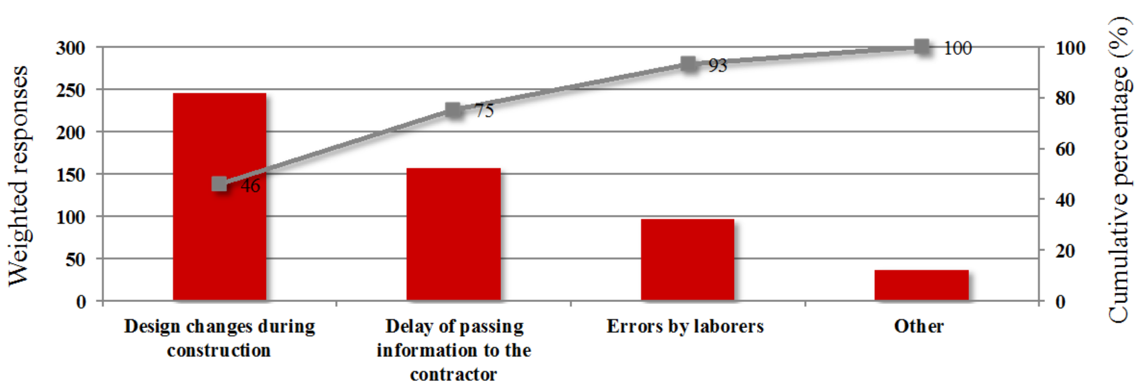


Figure 7 Pareto Chart: Factors that generate most waste according to questionnaire for the pile cap process

The questionnaire results compared well with causal factors found in the literature (Bossink and Brouwers 1996; Formoso, Soibelman et al. 2002; Rojas and Aramvareekul 2003;

Poon, Yu et al. 2004). A majority of on-site workers concurred that reducing or eliminating the likelihood of design changes during construction would help increase process performance by reducing waste. This might be achieved through establishing clear communication between involved parties, especially during the early phases of the project. Finally Step 3, Control, retrospectively evaluates the achieved process performance as well as techniques and strategies implemented in order to develop improved procedures for better performance in the future. Step 3 is essential to the framework: this step is responsible for maintaining consistent successful performance and for allowing continuous improvement.

To recap, this framework enabled us to apply the concept of DMAIC to the construction phase to improve the process. As demonstrated above, the sequence of steps starts with evaluating a chosen process, identifying the waste generated during the process, and measuring its impact. In this study, two types of waste were recognized: the ordering of too much materials and delays in the process schedule. During the second step, through the use of Six-sigma tools, we were able to identify 16 possible reasons for the generation of waste deriving from various sources. The 16 causes were narrowed down to the 3 most common causes via a questionnaire that was developed and sent to a consultant company. Because of that, we were able to find suitable solutions to implement to overcome these three causes. Finally, the success of these solutions was monitored and revised business processes were established to maintain improved performance.

3.6 CONCLUSIONS AND FUTURE WORK

Waste management has become a necessary task in the construction industry due to the abundant amount of waste generated by construction activities every year. For objective one, we explained a framework developed to identify and reduce waste during construction processes by integrating three methods: Lean, Green, and Six-Sigma. A case study of the installation of pile caps process was implemented to illustrate and validate the framework. In the Lean stage, the two categories of waste in the pile cap process studied were found to be waste in terms of materials and waste in terms of time. In the Green Stage, the associated environmental impact of the pile cap process was analyzed using common TRACI impact categories. The consumption of materials was the highest contributor to most impact categories including contributing to global warming, being carcinogenic, having respiratory effects, depleting ozone, and contributing to ecotoxicity. In the Six-Sigma stage, potential causes of waste were identified, then validated and ranked using a questionnaire that was administrated to a construction consulting company. The root cause, responsible for 46% of waste occurrences during the construction phase, was identified as "Design changes during construction" by questionnaire respondents.

The framework presented here has been designed to improve process performance during the construction phase of projects by reducing waste through a retrospective diagnosis. Errors and mistakes happen most of the time during construction due to the inherent complexity of the process. Typically, projects go through five phases: programming, design, construction, operation, and demolition. For future work the authors are proposing to develop a prospective model incorporating Lean, Green, and Six-sigma tools to prevent waste by diagnosing in advance the planned processes likely to produce waste. Improved planning and enhanced control during the earliest phases of the project have even greater potential to decrease the expense and environmental impacts of waste; or, to extend the medical metaphor, “An ounce of prevention is worth a pound of cure”.

4.0 APPLYING THE LEAN, GREEN, AND SIX-SIGMA FRAMEWORK TO IMPROVE AN EXTERIOR CONSTRUCTION PROCESS IN SAUDI ARABIA

The following chapter was submitted to the *Journal of Construction Engineering and Project Management,* with citation:

Banawi, A., Bilec M. (2013). "Applying Lean, Green, and Six-Sigma Framework to Improve Exterior Construction Processes in Saudi Arabia."

4.1 ABSTRACT

Over the last decade, Saudi Arabia has experienced significant economic increases, as evidenced by the 30% growth in its gross domestic product; furthermore, the construction industry has increased 10% in the same time period (S. A. Minstry of Finance 2011; Saudi National Commercial Bnak 2011). Due to this significant growth, the construction industry is encountering issues related to construction quality, resulting in significant waste and associated environmental impacts. In this research, we applied our previously developed framework that integrates three different methods—Lean, Green, and Six-sigma – to a residential construction complex in Saudi Arabia. Our aim with this case study was to explore the application of the framework in practice to glean quantitative results and further validate the framework. In the case study, we used the developed framework to identify a significant issue related to quality and delays, i.e., final completion of 53 residential units was delayed because of failed exterior buildings surfaces. We then used the framework to define the causes behind the defects via a field investigation of the 53 units. We found that construction execution was responsible for 43%; untrained workers, 31%; unfavorable construction weather conditions, 19%; and other issues accounting for 7%. A procedure was developed in concert with the construction manager and overall developer to reduce the amount of work having to be done again and the amount of waste revealed by the field examination and the framework. Although two steps were added to the original construction process to overcome the causes of the waste, a lot of resources were nonetheless saved and the environmental impacts were reduced. In summary, we found that the Lean, Green, Six-sigma framework allowed increases in productivity and quality, and reduction in waste.

4.2 INTRODUCTION

The construction industry has a major impact on economic growth. In developing countries such as Saudi Arabia, the construction sector is essential to short- and long-term economic growth. In 2010 the construction industry accounted for 11% of Saudi Arabia's Gross Domestic Product (GDP) at $300 billion. Saudi Arabia's GDP growth is the highest the country has experienced in the last several years. Many projects in various sectors have been constructed, with many more projects still in the planning phase. Some current construction projects include 36,800km of new roads, new airports, and additional berths in ports (S. A. Minstry of Finance 2011). Unfortunately, the rise in construction activity has also led to a host of construction issues - shortages of equipment, trained workers, and materials; sub-prime scheduling of activities during significantly higher temperatures.

Environmental protection to some countries is an integral aspect to long-term strategic planning, legislation, and executive orders. While a host of environmental issues exists, some of the most pressing ones include non-renewable energy usage, climate change, waste generation, poor water quality and insufficient availability of water and other natural resources, all of which are exacerbated by the increasing global population. The construction industry is a primary consumer for natural resources. In Saudi Arabia, for example, the demand for cement reached about 36.7 million tons, one third of US cement consumption in 2008 (Saudi National Commercial Bnak 2011; Portland Cement Association 2012).

With the high amounts of construction activity and the creation of poor-quality products, the Saudi construction industry is faced with the dual issue of excessive production of waste and excessive use of natural resources. Even though a significant portion of the municipal waste stream in Saudi Arabia is from construction, the government exercises minimal efforts to reduce waste in this area. Looking at various sources; including waste management facilities, municipalities, and construction companies, reveals a lack of data and information regarding construction waste in Saudi Arabia (Al-Jarallah 1983; Assaf and Al-Hejji 2006; Al-Nagadi 2007; Al-Sudairi 2007).

To address this problem, we applied our framework, an integration of three different methods—Lean, Green, and Six-Sigma, in a systematic approach, with the goal of reducing waste and thereby reducing the associated environmental impacts of the construction process (Banawi and Bilec 2013). Our aim was to illustrate via a residential development project in Saudi Arabia that all three methods in concert have the potential to minimize impacts generated by construction activities while improving quality.

4.3 METHODOLOGY

The overall framework is based on Six-sigma's Define, Measure, Analyze, Improve, Control (DMAIC), previously discussed in Banawi and Bilec (2013). To briefly summarize: *Steps 1a* and *1b*, *Define* and *Measure* - after selecting a construction process for evaluation, concurrently apply both Lean (VSM) and Green (LCA) to determine if waste is generated in the process and then to quantify the environmental impacts of the waste; ***Steps*** *2a* and *2b, Analyze* and *Improve* - if the process generates waste, then select and apply one or more appropriate Six-sigma tools to eliminate or reduce waste. Essentially, the framework contains Six-sigma tools nested within *Step 2*. For example, in this research a Pareto Chart and Process improvement were the selected Six-sigma tools; however any Six-sigma tool(s) could be executed in *Step 2* based on the case

Six-sigma tools; however any Six-sigma tool(s) could be executed in *Step 2* based on the case needs; *Step 3, Control* - Re-evaluate using Lean (VSM) and Green (LCA) to determine the extent of waste reduction. Each step is illustrated below in the case study.

4.3.1 Case Study

A case study was done to improve the construction processes for a residential complex in Madinat Yanbu Al-Sinaiyah (MYAS), Saudi Arabia and to illustrate the functionality of the framework. The case study "test" was simple to test the framework. MYAS is one of two industrial cites currently being established in Saudi Arabia to support the oil industry. MYAS is the western destination of oil and gas pipelines that start from the production area in the east of the Kingdom, and it is the largest port for exporting oil to the Red Sea. MYAS is an attractive business destination to many major oil investors from inside and outside the country. Therefore, construction in this area is a high priority on the Royal Commission for Industrial Yanbu's (RCIY) agenda, with the aim of providing services required by residents such as those related to housing, industry, health, education, recreational and public needs.

Prior to applying the framework, an on-site inspection was conducted over a total of two months, June to August 2012. During the on-site inspection and data collection phases, the framework was introduced and explained to the both the construction project manager and the RCIY project manager. On-site investigating of all study units was completed to identify the major issues of project delay and rejection by owners.

The framework was then applied to help analyze and ameliorate the root causes behind the appearance of paint blistering on buildings surfaces, shown in Figure 8. Fifty-three residential units, covering a total of 498,664 sf, were investigated in this case study. The exterior painting construction process evaluated in this case study consisted of three simple steps: (1) applying cement plaster, (2) applying primer sealer, and (3) applying paint.

Figure 8 Photos highlighting exterior quality issues

4.4 RESULTS AND DISCUSSION

To explain the implementation of the framework, we review each step in the process as each plays an important part in obtaining results:

Step 1a*: Value Stream Map**: For *Step 1a,** a Value Stream Map (VSM) was developed in order to identify, for each step of the exterior painting processes, where waste occurred (see Figure 9). The VSM was organized into four major elements: (A) project management, (B) the exterior painting construction process, (C) supplier, and (D) customer. The VSM systematically illustrates the relationships between the actors, data flow, and logistics. As illustrated in the VSM, the painting construction process consisted of three steps, with duration of 53-55 days. Lead/total time was a combination of Non-Value Added Time (NVA/T) or the time the process was on hold; and Value-Added Time (VA/T), the time the process was in progress. The NVA/T was 4 to 6 business days while the VA/T was 49 business days; furthermore the VSM explains the resources the process consumed including labor hours, materials and equipment. Finally, the VSM shows that units were rejected by owners due to the appearance of painting blistering on the building surfaces.

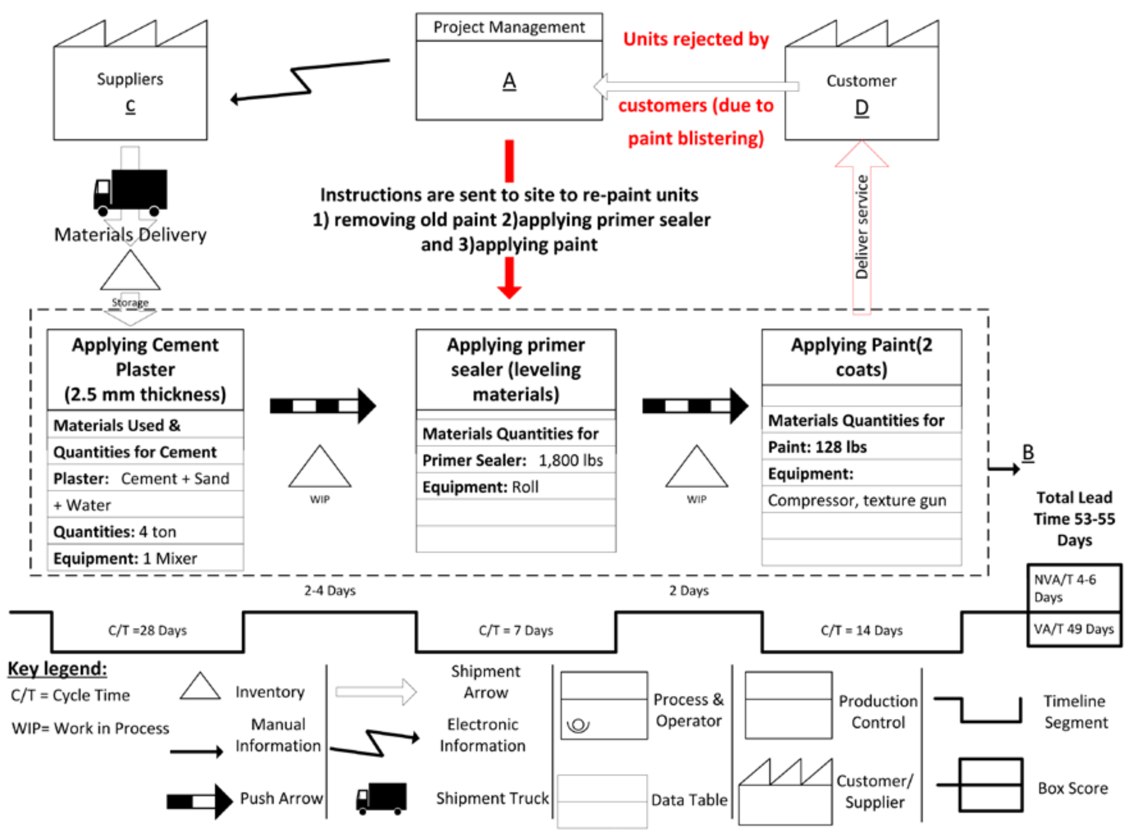


Figure 9 Value Stream Map (VSM) of case study exterior painting process

***Step 1b*, Greening:** For *Step 1b*, Greening, LCA was used to evaluate the environmental impacts of the exterior painting construction process. The LCA system boundary for the exterior painting construction process includes raw materials extraction and manufacturing; transportation of equipment, materials, and workers to and from the site; and equipment usage on-site. LCA was used to quantify the *original* process, and subsequently, the modified/improved process to understand the reduction in the environmental impacts. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI 2 V3.01) was used to perform the life cycle impact assessment (LCIA). The life cycle inventory data used is shown in Table 3.

Table 3 Life cycle inventory, data sources and remarks for exterior painting process

Note:
Original Process (OP) consists of: 1) applying cement plaster, 2) applying primer sealer, and 3) applying paint.
Modified Process (MP) consists of: 1) *pre-plastering*, 2) applying cement plaster, 3) *cleaning surfaces*, 4) applying primer sealer, and 5) applying paint.
Rejected Process (RP) consists of: 1) applying cement plaster, 2) applying primer sealer, 3) applying paint, 4) Removing old paint, 5) applying primer sealer,6) applying paint.

Construction Related Activity				Remarks	Data Sources	References
Transportation	Miles Traveled					
	Original Process	Modified Process	Rejected Process			
Operation, lorry 16-32t, EURO/RER S	25	25	50	Included in analysis: fuel consumption, direct airborne emissions of gaseous substances, particulate matter, heavy metals. Particulate emissions comprise exhaust and on-road emissions. Heavy metal emissions to soil and water caused by tire abrasion are included.	Ecoinvent system process	(SCLCI 1997)
Operation, passenger car, diesel, fleet average 2010/CH S	261	261	522	Included in analysis: fuel consumption, direct airborne emissions of gaseous substances, particulate matter, heavy metals. Particulate emissions comprise exhaust and on-road emissions. Heavy metal emissions to soil and water caused by tire abrasion are included	Ecoinvent system process	(SCLCI 1997)
Equipment	Fuel usage (Gallons)					
	Original Process	Modified Process	Rejected Process			
Concrete Mixer, Gasoline equipment 8.4 HP	37	50	55	Data for cradle-to-gate resource requirements and emissions for the combustion of 1000 gallons of diesel fuel in industrial equipment. Average USA technology, late 1990's.	Franklin USA 98	(Sylvatica 2004)
Air Compressor, Gasoline equipment 2 HP	20	20	40	Data for cradle-to-gate resource requirements and emissions for the combustion of 1000 gallons of gasoline in industrial equipment. Average USA technology, late 1990's.	Franklin USA 98	(Sylvatica 2004)
Materials	Material usage					
	Original Process	Modified Process	Rejected Process			
Paint ETH S	128 lbs	128 lbs	256 lbs	Transport of raw materials and production of paint. Packaging is not included.	Ecoinvent system process	Project estimates
Cement mortar, at plant/CH S	4 ton	5 ton	n/a	Manufacturing processes to produce cement mortar (raw materials provision, raw materials mixing, packaging, and storage), transport to plant, and infrastructure. No requirements for administration are included. No additional buildings and land-use have been taken into account. It is assumed that the mixing process takes place in an existing building of the sand/cement industry or on the construction site.	Ecoinvent system process	Project estimates
Base plaster, at plant/ CH S	1,800 lbs	1,800 lbs	2,592 lbs	Manufacturing processes to produce base plaster (raw materials provision, raw materials mixing, packaging, and storage), transport to plant, and infrastructure. No requirements for administration are included. No additional buildings and land-use have been taken into account. It is assumed that the mixing process takes place in an existing building of the sand/cement industry or on the construction site.	Ecoinvent system processes	(SCLCI 1997)

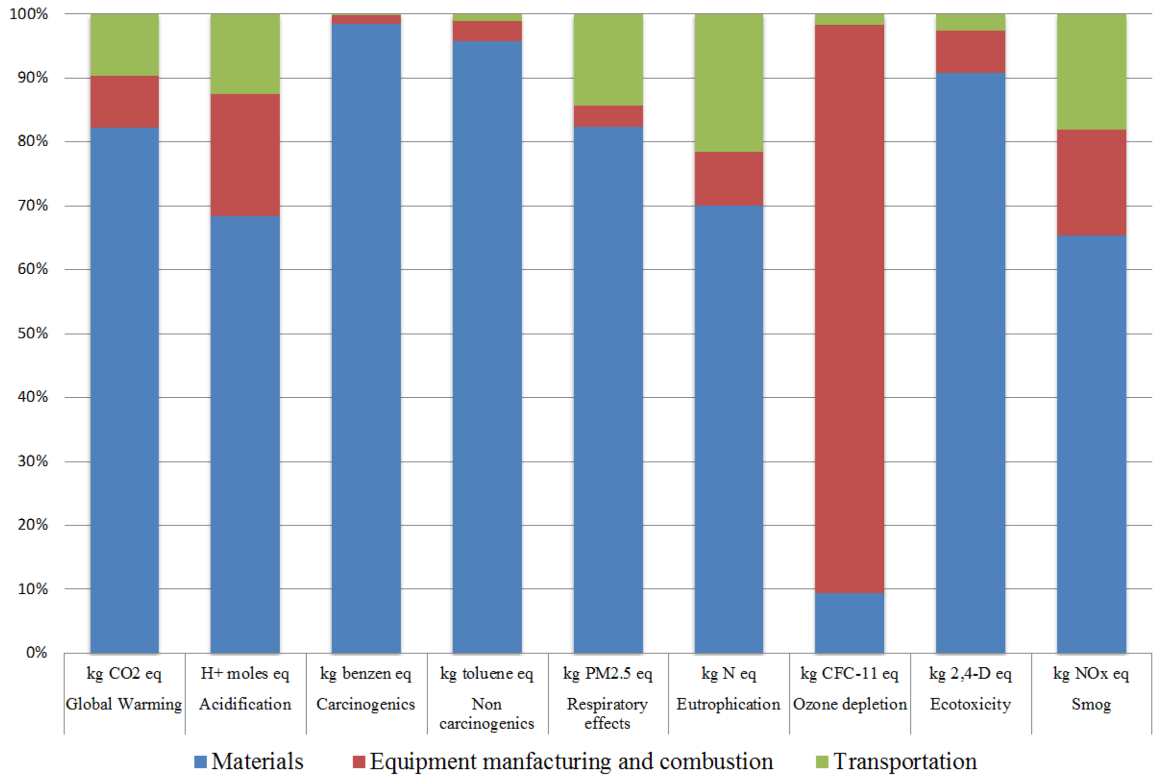


Figure 10 Life cycle environmental impacts for the original exterior painting process

The LCA results of the exterior paint process for nine environmental impact categories are shown in Figure 10 for three phases: Materials, Equipment manufacturing and combustion, and Transportation. Of the general environmental impacts, materials contributed to the highest share of impacts in all of the categories except for Ozone depletion, where Equipment manufacturing and combustion was the highest. From a closer analysis of the overall LCA results, cement manufacturing was a significant contributor to environmental impact from materials while paint came in second, as shown in Figure 11. Equipment manufacturing and combustion and Transportation each had the second highest impact in four categories: Equipment manufacturing and combustion came second in term of Acidification, Carcinogenic, Noncarcinogenic and Ecotoxicity while Transportation was the second highest in Global warming, Respiratory Effects, Eutrophication, and Smog.

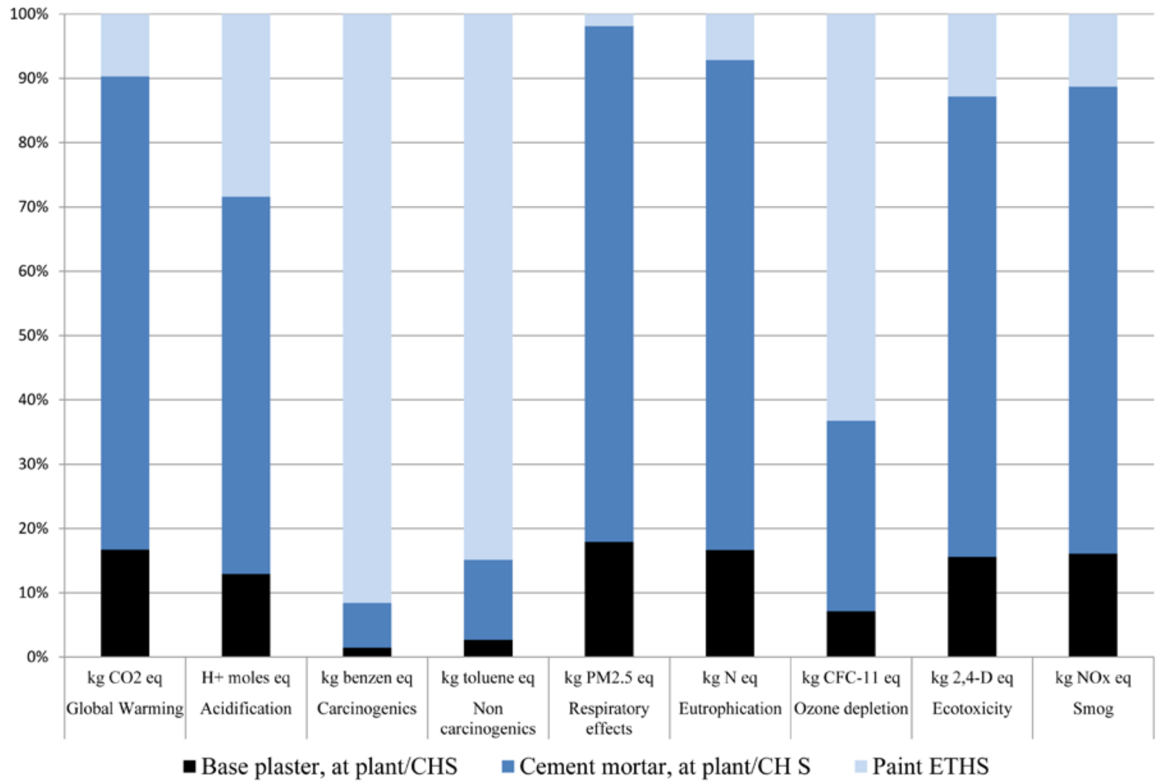


Figure 11 Life cycle environmental impacts for materials consumed for the exterior painting process

Step 2, Analyze and Improve: For *Step 2, Analyze* and *Improve*, the Six-sigma process improvement method was implemented, using a Pareto chart to analyze and identify the most commonly occurring causes that led to blistering. Then, Process improvement was used to create an alternative process that could minimize the variables' occurrence. In order to identify the variables causing blistering, an evaluation of 53 residential units was performed. Out of these 53 units, 10 units exhibited minimal blistering while the remaining 42 units had extensive blistering. A data sheet and site observations were used to collect data for the Pareto chart (see Appendix C.2).

Examining the units to identify the major causes of blistering was a time- and effort-intensive task. The units had to be carefully examined and the contractor project manager and the RCIY project manager had to be present and participating. Different parties were asked for their feedback regarding the low quality of the painting, including superintendents, project engineers, foremen, and workers. After final analysis of the data collected from the site, four major factors of blistering were observed: inadequate application (43%), untrained workers (31%), unfavorable weather conditions (19%), and others (7%), see Figure 12.

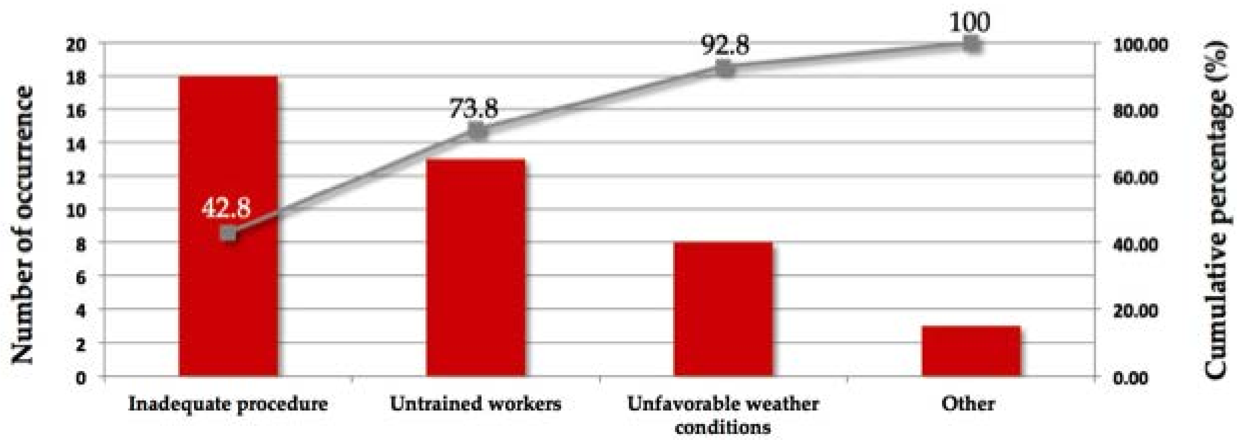


Figure 12 Pareto chart with factors that generate waste as identified by the field investigation of 53 units for the exterior painting process.

The Process improvement method was then used in order to improve the *original* process and to reduce the defects causes revealed by the Pareto chart. The main objective of the modified process was to eliminate or minimize the occurrence of blistering. Therefore, all four causal factors were considered at the time the modified process was created. The modified process includes two additional steps: (1) *pre-plastering*, (2) applying cement plaster, (3) *cleaning surfaces*, (4) applying primer sealer, and (5) applying paint *with adequate wait time*. The pre-plastering step involves adding bonding materials to minimize humidity transfer to surfaces. Humidity (included in cause “unfavorable weather conditions”) was shown to be a major cause of the blistering and resulted from the fact that more water was added to the concrete during construction because of the high temperature in order to slow the curing process. The other new step was cleaning the surface before applying the primer. Due to the climate of the area, dust is a major issue, especially in the summer season. The dust particles co-mingle with the paint, contributing to blistering. Both processes are obvious solutions that nonetheless had been neglected during the original process. Lastly, an increase in wait time from 2 days to 4 days was made before the last step of applying paint.

Figure 13 shows the current VSM for the modified process, including the additional two steps and all other data related to the exterior painting process. In collaboration with the construction management team, the modified process was successfully applied to two residential units. Both units were carefully examined and both showed no signs of blistering (see Figure 14).

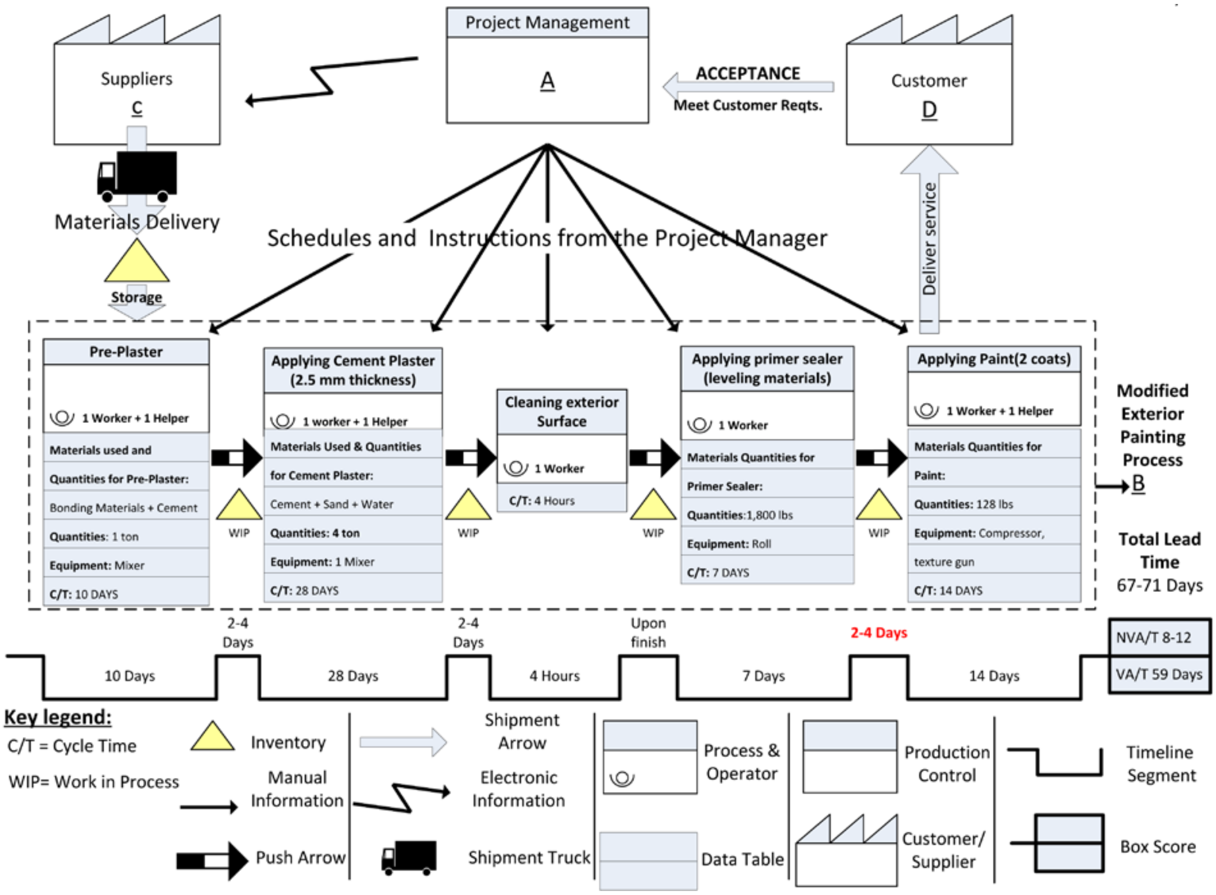


Figure 13 *Modified* Value Stream Map (VSM) for the exterior painting process

Figure 14 Examples of the modified painting process outcomes

Finally ***Step 3***, ***Control***: for this step, we retrospectively evaluated the achieved process performance as well as techniques and strategies implemented in order to develop improved procedures for better performance in the future. Step 3 is essential to the framework: this step is responsible for maintaining consistent successful performance and for continuous improvement.

The modified process was able to deliver a consistent construction process, and one designed to overcome unfavorable weather conditions and changing labor force. While the modified process did require more time and more resources than the original process, the modified process was the environmentally preferable option when compared to the original process plus rejected work. The rejected process' environmental impact includes the original process environmental impact plus the environmental impact generated from *repeating* two steps: 1) applying base plaster and 2) applying paint (see Table 4).

Table 4 Life cycle environmental impacts and time duration of the original painting process, modified process and rejected process

Impact Category	Unit	Original Process (OP)	Modified Process (MP)	Rejected Process (Including OP)
Global Warming	kg CO2 eq	1291	1510	1634
Acidification	H+ moles eq	194	222	276
Carcinogenics	kg benzene eq	9	9.6	18
Non carcinogenics	kg toluene eq	29409	30505	54266
Respiratory effects	kg PM2.5 eq	0.5	0.6	0.64
Eutrophication	kg N eq	0.26	0.3	0.34
Ozone depletion	kg CFC-11 eq	0.001	0.001	0.002
Ecotoxicity	kg 2,4-D eq	681	802	837
Smog	kg NOx eq	2.7	3	4
Number of steps		3	5	6
Duration (Days)		53-55	67-71	77

To recap, this framework enabled us to apply the concept of DMAIC to the construction phase to improve the process. The sequence of steps started with evaluating a chosen process, identifying the waste generated during the process, and measuring its impact. Then, through the use of Six-sigma tools, we identified possible reasons for the generation of the waste and found suitable solutions to implement. Finally, we monitored these solutions and revised business processes established to maintain improved performance.

4.5 CONCLUSION

Saudi Arabia is experiencing a boom in the construction industry, yet it is facing many challenges that could impact the industry's environmental performance. This paper explains a previously developed framework that can be used to identify and reduce waste during construction processes by integrating three methods: Lean, Green, and Six-Sigma. A case study of construction process of applying exterior painting in a residential complex in Saudi Arabia was implemented to further illustrate and validate the framework. A major defect, blistering, was identified. The associated environmental impact of the painting construction process was analyzed using TRACI impact categories. The consumption of materials was the highest contributor to most categories including Global Warming, Acidification, Carcinogenic, Non Carcinogenic, Respiratory Effects, Eutrophication, Ecotoxicity, and Smog. Potential causes of waste were identified, then validated and ranked, using a Pareto Chart. The root causes responsible for the blistering occurring during the construction phase were identified as "inadequate procedure" accounting for 43%, "untrained workers" at 31%, "unfavorable weather conditions" at 19%, and "others" at 7%. A modified process was developed to eliminate potential causes by applying the Process improvement method. The modified process was then implemented on two residential units for validation. The modified process was able to deliver units that are blistering less.

In the future the Lean Green, Six-Sigma framework will be modified to allow it to be a part of the quality inspection procedure for buildings during construction. To achieve that, the framework should take less time and effort than what it does now, yet should deliver the desired results. The successful attempts in this study will be introduced to several organizations in Saudi Arabia to encourage the industry to consider revaluating their own processes for a better quality environmental performance.

5.0 A MODEL COMBINING THE THREE METHODS LEAN, GREEN, AND SIX-SIGMA (LG6) TO IDENTIFY WASTE IN CONSTRUCTION PROCESSES PRIOR TO CONSTRUCTION PHASE

5.1 ABSTRACT

The construction sector is a major contributor to negative environmental impacts in the United States and furthermore consumes an abundant quantity of natural resources---. In this research, an innovative model was developed with the goal of improving the life cycle environmental impacts of buildings by identifying potential waste sources prior to the construction phase, in the earliest stages of a project. The new model, called LG6, integrates three methods - Lean, Green, and Six-Sigma - and implements the Define, Measure, Analyze, Improve, and Control (DMAIC) improvement framework to environmental improvement, waste and cost reduction in construction.

The functionality of LG6 is illustrated through a case study of a woodpile installation construction process. In this case study, the LG6 model identified four steps out of eight as non-value added steps or potential waste generators according to the Lean principles. Three of the four steps involved extra time and effort by the contractor to set up equipment, while the fourth involved additional work that could have been avoided with adequate planning. For the case study, the LG6 model showed that environmental impact could be reduced by 9%—and expenses

reduced by 1% as well—if alternative processes had been implemented. Specifically, the alternatives suggested would have minimized the environmental impacts of major contributors of materials, transportation, and equipment usage, in addition to helping reduce the residual waste that occurred from cutting to length all woodpiles. Quality, Costs & Impacts Process Analysis demonstrates that this case study shows the usefulness of the LG6 model on a single process and suggests that much unnecessary waste could be avoided if the LG6 model were applied extensively during pre-construction.

5.2 INTRODUCTION

Activities related to the construction industry have a considerable environmental impact in the United States: Total construction and demolition (C&D) waste in the US was estimated to be 325 million tons in 2003 (U.S. Environmental Protection Agency 2004). Unfortunately efforts to reduce C&D waste have not been very successful to date. One reason for this is that while contractors have different methods of completing their jobs, usually relying heavily on their own experience, for most, success is defined as finishing the job within the given constraints of money, time, and quality. Although contractors may typically finish within the budget and the time frame they are given, their construction methods may generate a significant amount of waste (Love, Edwards et al. 2009).

Another reason it is difficult to reduce waste in the construction process is that the nature of the construction industry is complicated: every project is unique and has a different purpose (Bossink and Brouwers 1996; Ekanayake and Ofori 2000); moreover, every project consists of multiple tasks that are usually assigned to separate crews involved with the project, with each having a high likelihood of contributing to waste generation. This fragmented nature of construction makes the likelihood of waste being generated at any point of the project phases greater. Therefore, it seems that environmental and economic benefits arising from the reduction of waste can best be achieved by proactively planning ways to prevent waste from being generated in a project in the first place *a priori*, rather than simply seeking to reduce it *ad hoc* on site during construction itself (Lee, Diekmann et al. 1999).

Several organizations have established rating systems to enhance the environmental performance of the built environment. For instance, the U.S. Green Building Council (USGBC) has developed the Leadership in Energy and Environmental Design (LEED) system, which awards points under several categories for the reduction of environmental impacts at corresponding points in a building's life cycle. Effective application of LG6 to a specific building project may result in the awarding of LEED points under the category for design innovation and the creation of new methods or tools to improve life cycle environmental performance (U.S. Green Building Council USGBC 2009).

This chapter presents an innovative *model* for the identification and minimization of waste and extends a previously developed conceptual framework (Banawi and Bilec 2013) by applying three proven methods at the *pre-construction bidding/planning phase*. The developed model can be applied to many construction processes without the need for trying new tools every time we evaluate a construction producer while the framework was developed with the capability to apply certain aspects that might differ from one process to another depending on the chosen process. An earlier conceptual framework was proposed and tested integrating three methods—Lean, Green, and Six-sigma—to eliminate waste *during* the construction phase through monitoring and continuous improvement strategies. This framework applies the 5-step Define, Measure, Analyze, and Improve, Control (DMAIC) process improvement approach to waste reduction and environmental impact improvement. Specifically, possible waste sources in each construction process are defined, then related environmental impacts are measured, root causes of waste analyzed, fundamental waste sources eliminated, and finally, process performance controlled to sustain success.

This present work applies the same three Lean, Green, and Six-Sigma (LG6) methods to enable contractors to proactively identify and eliminate potential waste *prior* to the construction phase. The hypothesis is that LG6 will reduce waste generation during the pre-bidding and bidding phases of construction projects, resulting in both decreased environmental impacts and lower costs. All three methods can be efficiently integrated into the project pre-construction phase: Lean to identify waste, Green to evaluate the environmental impact of potential waste, and Six-Sigma to evaluate and improve process performance. The objectives to achieve by developing the LG6 model are:

1) Helping stakeholders reduce environmental impacts of buildings prior to construction.
2) Decreasing the overall environmental impacts and carbon footprint of the construction industry.
3) Increasing awareness of green initiatives and the value of their application to the construction industry.
4) Creating a tool for buildings to be awarded LEED points.

To illustrate how LG6 was used to accomplish these main research objectives and what was learned from this research, this chapter presents a brief background of the incorporated methods, details the improvement model and its structure, discusses a case study, and concludes with recommendations for LG6 implementation and future research.

5.3 RESEARCH METHODOLOGY

The work consists of developing a proactive model and executing a case study to examine the validity of the LG6 model. Excel, a well-known and easy-to-use software tool, was used to construct the LG6 case. The model is available for download at http://www.engineering.pitt.edu/SGD/.

5.3.1 Lean Green Six-sigma (LG6) Model

The LG6 model has two parts (Figure 15): *Level one:* contains the basic information about the construction process under consideration, including the name, scope of work, date, client information, and project requirements. Some main points about the three methods Lean, Green, and Six-sigma are listed at Level One of the LG6 model, where it is essential to give the user a reminder of what the purpose of each method is. *Level two:* Divided into five functions, based on the DMAIC stages:

5.3.1.1 Define

The Define phase identifies the starting date of each step, its incremental duration, and the total duration of the construction process. It is important for contractors to layout all the steps they usually follow in finishing a certain job so that each step can be evaluated individually to determine to what extent it absorbs resources and generates waste.

5.3.1.2 Measure

This phase consists of quantifying all consumed resources (materials, equipment, and manpower) for each step in the process as well as their associated costs. Fuel consumption by equipment and task was aggregated under the equipment section in order to more easily quantify the fuel-related environmental impacts.

5.3.1.3 Analyze

In this phase, all steps are evaluated using both Lean and Green criteria. First, applying the Lean "value-added" concept, the contractor needs to identify any steps in the process that consume resources without generating value. These should be eliminated or modified to achieve a more lean process.

Second, as every step in the process consumes resources and is responsible for producing some share of the total emissions, the LG6 model applies Green/LCA to quantify the specific incremental environmental impacts generated by each step in the process. To help the user calculate the environmental impact, the LG6 model provides a summary of the most common materials used in construction, such as concrete, steel, blocks, etc. along with the characterization factors for associated environmental impacts. Using values generated in databases from the SimaPro7 software (Goedkoop and Oele 2008), these characterization factors represent the magnitude of impact per single unit in each specific impact category. For example, the global warming potential of steel is 1.049 grams of CO_2 equivalent per kilogram of steel used, and the Acidification potential is 0.517 grams of H+ moles equivalent per kilogram of steel used. This conversion process allows the aggregation of impacts from every step in the process, resulting in a single value for the overall process in each environmental impact category (see Appendix C).

5.3.1.4 Improve

In this phase, the process owner has the opportunity to consider alternatives that offer better performance in terms of efficiency, economy and/or specific environmental impacts. Considering the outputs from the Define, Measure, and Analyze stages, the contractor can now easily identify which steps in the process are most wasteful of time and money and which have the greatest associated environmental impacts. For example, an improvement might be to use pile-driving equipment that requires less fuel so as to generate fewer emissions (and simultaneously save on fuel costs); another suggestion might be to eliminate a non-value adding step to reduce labor and fuel costs as well as related emissions.

5.3.1.5 Control

The purpose of the control stage is to keep performance at a targeted level. The LG6 uses the Defect Per Million Opportunities criteria to measure the overall performance of the process. Applying the DPMO tells how efficiently the process is performing according to the Six-sigma scale. The output from DPMO is converted to a sigma level, where the more closely the value approaches the number 6, the fewer defects the process will generate.

Level 1

The installation of woodpiles process	Start	Finish
Scope of Work:		

Level 2

(D) Define			(M) Measure			(A) Analyze												(I) Improve	(C) Control		
						Lean		Green	Environmental Impact Categories												
Start Date	Process Steps	Units	A- Materials	B- Equipment	C- Workers	Value added step	Non-Value added step	Source of impact	1	2	3	4	5	6	7	8	9	Alternatives with less potential impact	Total # of Steps	Total # of non value added Steps	DPMO
	D.1-		M.1.A-	M.1.B-	M.1.C-	*		A.1-										I.1-			
	D.2-		M.2.A-	M.2.B-	M.2.C-	*		A.2-										I.2-			
	D.3-		M.3.A-	M.3.B-	M.3.C-	*		A.3-										I.3-			
	D.4-		M.4.A-	M.4.B-	M.4.C-		*	A.4-										I.4-			
Total duration HRS:			Total cost $:					Total emissions:													
Non-value added duration HRS:			Total cost for non value-added steps $:																		

Keys Legend:
Environmental Impact Categories:
1: Global Warming potential (CO_2)
2: Acidification Potential (H+moles)
3: Carcinogenics Potential (benzene eq)
4: Non-Carcinogenics Potential (toluene eq)
5: Respiratory Effects Potential ($PM_{2.5}$ eq)
6: Eutrophication Potential (N eq)
7: Ozone-Depletion Potential (CFC-11 eq)
8: Ecotoxicity Potential (2.4-D eq)
9: Smog Potential (NO_X eq)

Figure 15 Outline, LG6 model

5.3.2 Case Study

A case study of the pile-driving process was generated to illustrate the functionality of the LG6 model. Specifically, the model was used to evaluate the process for furnishing and driving approximately 160 woodpiles that were 40 feet long, 14 inches in diameter at the base and 7 inches at the tip into normal soil. This case study was taken from a project recently completed by a local contractor for a commercial building project in Pittsburgh, PA. All data regarding the cost of the construction process including materials, workers, transportation and time schedule was provided by the contractor.

5.4 RESEARCH FINDINGS AND RESULTS:

5.4.1 Define (D)

For the sample case, a total of eight steps and 88 hours were estimated to be required to finish furnishing and driving 160 woodpiles. The identified steps were: delivering the materials to the site, driving the equipment to the site, setting up the equipment, taking down the equipment, moving out the equipment, driving the piles, cutting to length, and cleaning up the site. The step of driving the piles was the most time-intensive, using 56 labor-hours; while cutting to length was second, requiring 16 hours of work (see Table 5).

Table 5 Define phase explains start dates, process steps and units for the woodpile installation process.

Define (D):			
Date start	**Process steps**	**Process Description**	**Value**
06/01	D.1	Delivering the woodpiles and the pile points to the job site	Distance: 50 miles
06/01	D.2	Driving the equipment to the job site	Distance: 30 miles
06/02	D.3	Setting up the equipment	Duration: 4 hrs.
06/02	D.4	Taking down the equipment	Duration: 4 hrs.
06/02,03	D.5	Moving out the equipment	Duration: 4 hrs.
06/04	D.6	Driving the piles	Duration: 56 hrs.
06/12	D.7	Cutting to length	Duration: 16 hrs.
06/14	D.8	Cleaning up the site	Duration: 4 hrs.
		Total Process Time Duration in Hours	88
		Non-Value added Total Time Duration in Hours	28
Key Legend:			
Non-Value Added Step		Value-Added Step	

5.4.2 Measure (M)

The next stage required an assessment of all resources consumed by each step in the construction process, including materials, equipment, and workers (Table 6).

A- Materials: Quantities and Cost: Only step D.1 “Delivering the woodpiles and the piles points to the job site” was estimated to consume significant quantities of materials: about 6720 ft. of woodpiles, and 160 steel pile points at a total cost of $83,795.

B- Equipment, fuel usage, and equipment cost: Both step D.1 “Delivering the woodpiles and the piles points to the job site” and step D.2 “Driving the equipment to the job site” was estimated to require trucks to deliver the materials (50 miles away) and the equipment (30 miles away) to the job site. The delivery costs for materials and equipment was estimated to be included by the vendor in their respective costs. Step D.6 “Driving the piles” was estimated to require equipment use representing a total equipment rental cost of $6859 and consuming a total of 4711 gallons of fuel. Step D.7 “Cutting to length” was estimated to use a power saw costing $523.60 for rental and consuming about 6 gallons of fuel.

C- Workers: no contractor workers were required for steps D.1 “Delivering the woodpiles and the piles points to the job site”, and D.2 “Driving the equipment to the job site”; however, the remaining steps in the process each did. Step D.6 “Driving the piles” required a crane operator (at a higher hourly rate) in addition to general laborers. The total cost for the workers for this process was estimated at $5371.

Table 6 Measure phase explains consumed resources for the woodpile installation process, including materials, equipment, and workers

Measure (M):				
Process steps	**Materials (A)**	**Quantities**	**Unit cost $**	**Total cost $**
M.1.A	1. 160 wooden piles (40 lin. ft.)	6720 ft.	11	72912
	2. Pile points	168 pieces	65	10884
M.2.A	NA			
M.3.A	NA			
M.4.A	NA			
M.5.A	NA			
M.6.A	NA			
M.7.A	NA			
M.8.A	NA			
			Total Materials Cost	**83,795**
			Total Materials Cost for Non-Value Added Steps	**0**
	Equipment (B)	**Fuel usage in gal.**	**Cost of equipment usage**	
			Unit cost $	**Total cost $**
M.1.B	1. NA			
	2. NA			
	3.A Truck for materials transportation	Include with materials cost		
M.2.B	1.A Truck for equipment transportation	Include with equipment cost		
M.3.B	NA			
M.4.B	NA			
M.5.B	NA			
M.6.B	1. Crane 800 HP. Diesel	2688	82.4	4614.4
	2. Leads for hammer	NA	14.63	819.28
	3. Pile hammer 600 HP. Diesel	2016	10.8	604.8
	4. Air compressor 3.0 HP. Gasoline	6.72	14.65	820.4
M.7.B	1. Concrete saw, Gasoline 5.6 HP.	5.4	9.35	523.6
M.8.B	1. Construction cleaning tools (brushes, brooms, etc.)	NA	NA	NA
			Total Equipment Cost	**7,382.5**
			Total Equipment Cost for Non-Value Added Steps	**523.6**
	Workers (C)	**Working Hours**	**Unit cost $/hr.**	**Total cost $**
M.1.C	NA			
M.2.C	NA			
M.3.C	1. (2) General laborers	4	15.56	124.48
M.4.C	1. (2) General laborers	4	15.56	124.48
M.5.C	1. (2) General laborers	4	15.56	124.48
M.6.C	1. (1) Crane operator	56	21.67	1386
	2. (3) General laborers	56	15.56	2987.52
M.7.C	1. (2) General laborers	[illegible]	15.56	497.92
M.8.C	1. (1) General laborers	1	15.56	15.56
			Total Workers Cost	**5,370.2**
			Total Workers Cost for Non-Value Added Steps	**871.4**

5.4.3 Analyze (A)

Each step of the woodpile installation process was then evaluated according to Lean criteria to determine if it added value and by Green criteria to calculate its environmental impacts in each category (See Table 7).

Lean: Four steps out of the total eight were recognized as non added-value steps, namely Step D.3 “Setting up the equipment”, Step D.4 “Taking down the equipment”, Step D.5 “Moving out the equipment”, and Step D.7 “ Cutting to length”. Cutting to length is a task that is responsible for the kind of materials residual waste typically found in most of the construction projects reported by EPA 2010 (U.S. Environmental Protection Agency 2003).

Green: Two major sources of potential environmental impacts in this process were identified: First the estimated materials —both wood and steel—have significant environmental impacts. Wood shows the highest aggregate impacts in categories such as Carcinogenics, Respiratory effects, Eutrophication, Eco-toxicity and Smog; while steel reflects greater impacts in the categories of Global Warming, Acidification, Non-carcinogenics and Ozone depletion. A second major source of impacts was fuel usage for both transportation and equipment operation. The crane operation was the highest contributor to Global Warming Potential while driving the piles ranked second (see Table 7).

Table 7 Analyze phase highlights value-added and non value-added steps and addresses environmental impact of the woodpile installation process.

Analyze (A):				
Lean			**Green**	
Process Steps	**Value-Added Steps**	**Non Value-Added Steps**	**Source of Potential Waste/Environmental Impact to be Analyzed by LCA**	**Inventories**
A.1	✔		A.1.1 Resources usage / Wood	6720 ft.
			A.1.2 Resources usage / Steel	2016 kg
			A.1.3 Transportation/ Diesel	50 miles
A.2	✔		A.2 Transportation/ Diesel	30 miles
A.3		✖	NA	
A.4		✖	NA	
A.5		✖	NA	
A.6	✔		A.6.1 Equipment usage/ Diesel	2688 gal
			NA	NA
			A.6.3 Equipment usage/ Diesel	2016 gal
			A.6.4 Equipment usage/ Diesel	6.72 gal
A.7		✖	A.7 Equipment usage/ Diesel	5.4 gal
A.8	✔		NA	

Green - Life Cycle Environmental Impact Categories									
Item	**Global Warming (CO_2 eq.)**	**Acidifica-tion Potential (H+moles eq.)**	**Carcinog-enics Potential (Benzene eq.)**	**Non-Carcinogenics Potential (Toluene eq.)**	**Respirato-ry Effects Potential ($PM_{2.5}$ eq.)**	**Eutrophicat-ion Potential (N eq.)**	**Ozone Depletion Potential (CFC-11 eq.)**	**Eco toxicity Potential (2.4-D eq.)**	**Smog Potential (NO_X eq.)**
A.1.1	-1065098	93808.84	98.9	970641.3	315	39.6	2.81E-06	20099.9	1279
A.1.2	2116	1044	62	110759	4	0.6	7.0825E-06	249	10
A.1.3	65	23	0.012	195	0.05	0.04	9.6911E-06	9	0.5
A.2	39	14	0.007	117	0.03	0.024	5.8146E-06	5.4	0.3
A.3	NA								
A.4	NA								
A.5	NA								
A.6.1	4683	3227	11	239336	5	2	1.3081E-06	6646	32
A.6.2	NA								
A.6.3	3512	2420	9	179502	4	1.7	9.8109E-07	4985	24
A.6.4	13	8.8	0.03	651	0.01	0.006	3.5594E-09	18	0.09
A.7	10	7	0.02	520	0.01	0.004	2.8444E-09	14	0.07
A.8	NA								
Total Emiss-ions	**-1054660**	**100552.8**	**181.2**	**1501721.5**	**327.6**	**44**	**2.7696E-05**	**32027.3**	**1345.7**

5.4.4 Improve (I)

In this stage, alternatives were generated to replace the previously proposed steps in order to improve the environmental performance of the woodpile process (See Table 8). It is not necessary that each step be replaced with a more efficient, environmentally friendly or less costly alternative; rather, the objective was to let the owner consider what specific alternatives might be applied that could reduce environmental impacts and improve the bottom-line. For instance, renting equipment or acquiring material closer to the job site could reduce fuel consumption, thus lowering costs and emissions. Another alternative is to standardize all piles to a single length if the topography of the site would allow. This would eliminate the necessity of the extra work needed to cut all woodpiles to length after driving them, thereby reducing manpower costs, materials used, fuel consumed and their related impacts.

Table 8 Improve phase discusses alternatives to the process with less environmental impact and better economic returns for the woodpile installation process

Improve (I):	
Process Steps	**Optional Alternatives (For better process performance)**
I.1.1	
I.1.2	
I.1.3	Purchase materials from a close providers (Less travel distance)
I.2	Rent equipment from a close providers (Less travel distance)
I.3	
I.4	
I.5	
I.6	
I.7	Consider wood piles with same length
I.8	

5.4.5 Control (C)

This stage evaluated via DPMO the revised method that the contractor actually implemented to finish installing 168 pieces of woodpiles. According to the Lean criterion, four out of the eight steps (50%) in the process were considered non value-added steps; because of this, the current contractor method performance would create 500,000 defects in every million attempts. On the Sigma metric this performance is equal to 1.5 (See Table 9).

Table 9 Control phase explains the current performance level according to the Six-Sigma scale for the installation of the woodpile process

Control (C):		
Total Number of Steps in The Process	**Total Number of the Value-Added Steps in The Process**	**Sigma Metric**
8	4	1.5

Finally, Table 10 shows a summary of major outputs for the woodpiles process, including basic data about the examined process, potential improvements in environmental impacts and possible saving costs.

Table 10 QCI Process Analysis - Results for the woodpile installation process - Quality, Costs & Impacts

QCI Process Analysis for Installation of Woodpiles			
Division	Foundation	**Process**	Installation of Woodpiles
Total number of steps in the process			8
Total number of non-value added steps in the process			4
Defective per million opportunities			500,000
Sigma Metric			1.5
Total process time (hrs.)			85
Time that might be saved in the process (hrs.)			28
Total process cost ($)			96,547.76
Total saving cost ($)			1394.96
Total saving in materials cost ($)			0
Total saving in equipment cost ($)			523.6
Total saving in workers cost ($)			871.36

Total Environmental Impact			
Impact Category	**Unit**	**Original process** Value-added steps + Non-value steps	**Modified Process** Value-added steps only
Global Warming	**(CO_2 eq.)**	(1054660.2)	(1054670.3)
Acidification	**(H+moles eq.)**	100552.8	100545.8
Carcinogenics	**(Benzene eq.)**	181.2	181.1
Non-carcinogenics	**(Toluene eq.)**	1501721.5	1501201.1
Respiratory effects	**($PM_{2.5}$ eq.)**	327.6	327.5
Eutrophication	**(N eq.)**	44.05	44.04
Ozone depletion	**(CFC-11 eq.)**	2.7696E-05	2.7693E-05
Eco toxicity	**(2.4-D eq.)**	32027.3	32012.8
Smog	**(NO_X eq.)**	1345.78	1345.71

5.5 CONCLUSION

Planning and carrying out projects in the construction industry is distinctly challenging in that many different resources have to come together to accomplish one goal and the many tasks involved must be completed in a cost-effective and minimally wasteful manner. Despite the potential conflicts between these two objectives on any given project, the construction industry has the opportunity to make improvements to both during each of the specific phases of a project. This research study seeks to create an innovative yet intuitive and easy-to-use model that can help improve environmental performance and bottom-line results of construction processes. Preventing waste before construction has greater benefits than trying either to eliminate waste "on the fly" or to remediate for it after construction.

For this purpose of preventing waste, a pro-active Lean-Green-Six Sigma improvement model (LG6) was designed to help contractors and process owners to re-evaluate their traditional construction methods during the bidding phase to decrease environmental impacts, inefficiencies and costs. In order to illustrate the LG6 model, a case study of installing 160 of woodpiles was examined. This single process required eight steps, 88 hours of total process time and $96,548 in total process costs, prior to implementation of any improvement strategies.

The LG6 model shows that four out of the total eight steps in the woodpiles process were non value-added, indicating that their elimination or replacement could enhance the performance of the process by up to twice as much. For instance, in the case study, acquiring woodpiles with the same length would eliminate the equipment usage and money required to cut all of the woodpiles to length. Also, the LG6 shows that the costs could be reduced by 1% and greenhouse gas emissions by 9% if the original process was revised to implement the suggested alternatives.

The case-study results in terms of savings might seem insignificant, yet the woodpiles process is only one construction process that is often integrated with other non-optimized processes. Evaluation of all of the steps in a project, then, and use of alternatives suggested by LG6 could result in more significant aggregate savings in money, time, and environmental impacts.

In conclusion, the LG6 model is a comprehensive, step-wise tool that can help any process owner to pre-plan the process, highlighting any potential waste generators early so they can be avoided. The LG6 model is easy to implement, provides tangible results, addresses multiple applicable alternatives, provides for performance control and continuous improvement, and above all, is proactive.

6.0 CONCLUSION

6.1 SUMMARY

This work exhibits the use and benefit of a novel approach to construction evaluation, combining three different approaches into one common system and using this system in an untapped sector to improve the environmental performance of the construction processes *during* and *prior* to the construction phase. The construction sector is a major materials consumer and major contributor to environmental impacts around the globe. For that purpose two methods were developed and applied during and prior to the construction phase, a 3-step framework and an improvement model. The two methods integrate Lean, Green, and Six-Sigma with the help of the DMAIC improvement model.

The 3-step framework was validated via a case study performed to evaluate and improve a pile caps construction process for an educational institute project in Pittsburgh, Pennsylvania. Two issues were revealed by the framework: extra inventory and a 23-day delay. Then, the environmental impacts of the pile caps process were analyzed using LCA. LCIA results show that the material for the pile caps construction process was the highest contributor to the environmental impact in five out of nine categories. The potential causes for waste in pile caps were collected and ranked through a survey developed for and administered by a construction consultant company in Pittsburgh. Results from the questionnaire suggested that 60% of the time

“Design changes during construction” leads to waste in projects, which matches what has been reported by professionals and industry in the literature.

The previous framework was further validated via a study looking at how to improve an exterior painting construction process for a residential complex in Saudi Arabia. A major defect, blistering, was identified. Then the associated environmental impacts of the painting construction process were analyzed. The materials production phase was found to be the highest contributor in almost all of the environmental impact categories. Potential causes of waste were identified and ranked using a Pareto chart as follows: Inadequate procedure at 43%, Untrained workers at 31%, Unfavorable weather condition at 19% and Other at 7%. A modified process was then developed using Process improvement method to overcome these variables and then applied to two units. The modified process was able to deliver units that were not rejected, reducing the overall project waste and associated environmental impacts.

A pro-active improvement model (LG6) was then designed to help contractors and process owners to reevaluate their traditional processes to decrease environmental impacts and increase the bottom-line prior to construction. A case study of installing 160 of woodpiles was implemented to examine the LG6 model. In order to finish this job, eight steps were required. The total process time was 88 hours and the total process cost was $96,547.76. The LG6 model shows that four out of the total eight steps in the woodpiles process were non value-added steps replacing these steps with better alternatives would enhance the performance of the process, where costs could be reduced by 1% and emissions by 9%.

6.2 RECOMMENDATIONS FOR FUTURE WORK

Construction is a challenging field, where activities require careful planning and effective management. As sustainability becomes more of an issue worldwide, in addition to meeting the budget and time estimates during early phases, projects must also now consider achieving other objectives such as reducing the environmental impacts of construction activities.

The framework and LG6 model developed in this study can help to achieve the desired benefits given two important conditions: first, the commitment of the upper management and all the people involved in any improvement effort must be obtained. Without their support and participation it is not possible to achieve improvements. A second important condition is that the implementation of improvement actions be carefully planned. Carefully implementing will require time and effort, yet it is very important for accurate results.

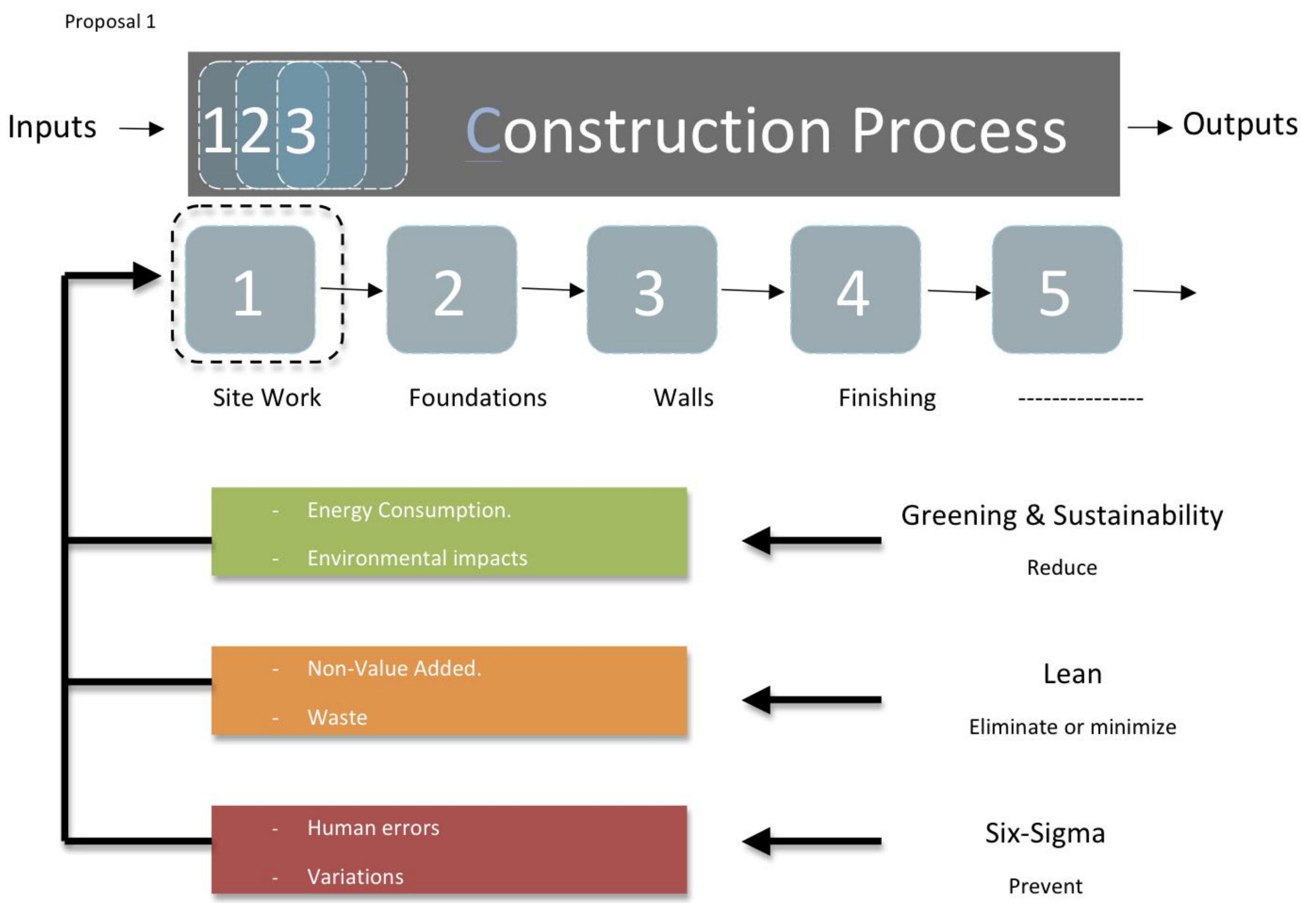
Aspects for future consideration are as follows: first is how to integrate these methodologies to be part of work producer in one of the early phases in a project, i.e., the planning, designing, or bidding phase, most effectively. Second is to consider applying these methodologies to Design-Build (DB) type of projects, where the contractor is involved with the process from the beginning as this might increase the benefits of applying the developed tool. A third possibility to consider is applying the methodologies to improve a construction process that is already known to be a major source of waste during the construction phase. Fourth, the construction firms might develop a plan that deals with extra inventory. Finally, the environmental impacts that change orders might be responsible for must be included as a consideration for decision-making on the part of the producer in addition to other concerns such as budget and time. Using the life cycle assessment method would help the decision makers evaluate change orders environmental impacts to reach a change order that has minimal environmental impact.

7.0 ACKNOWLEDGEMENTS

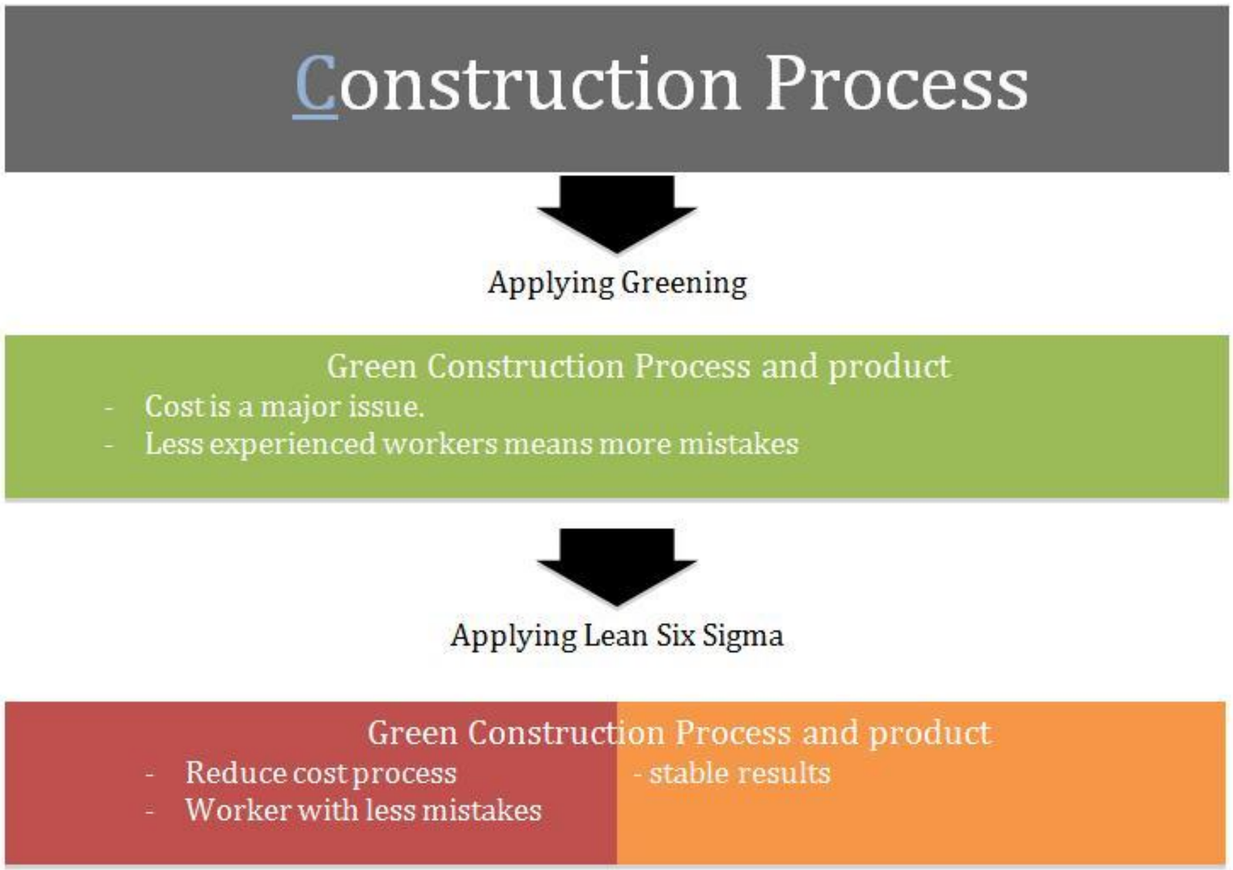
The authors wish to thank the Ministry of Higher Education, Saudi Arabia for the support and efforts provided through King Abdullah Scholarships Program. Also the authors would like to thank the Royal Commission of Industrial Yanbu for their help providing data for the case study in this research.

APPENDIX A

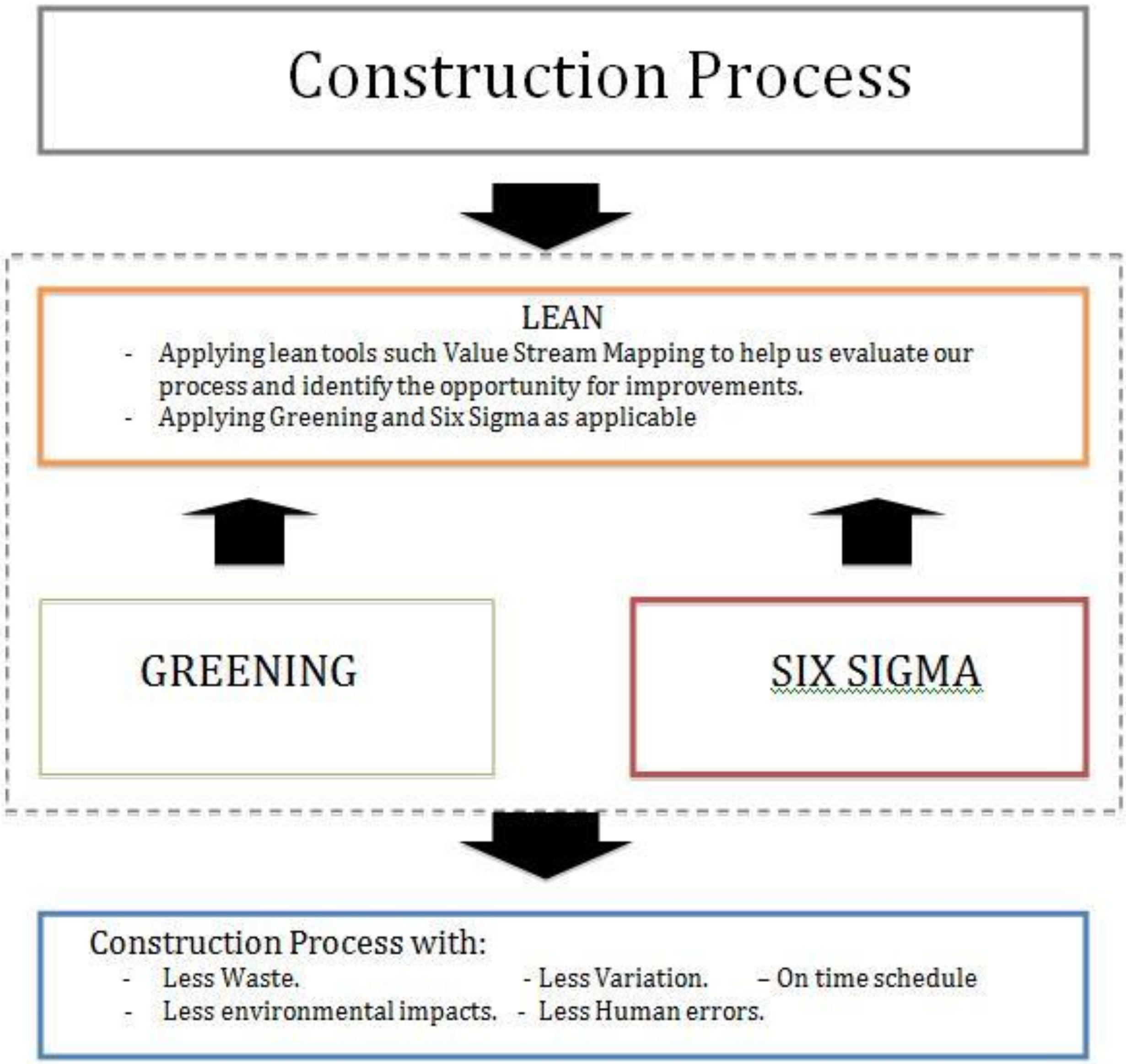
A.1 PROPOSAL 1, LEAN, GREEN, AND SIX-SIGMA FRAME WORK



A.2 PROPOSAL 2, LEAN, GREEN, AND SIX-SIGMA FRAME WORK



A.3 PROPOSAL 3, LEAN, GREEN, AND SIX-SIGMA FRAME WORK



APPENDIX B

B.1 CASE STUDY: QUESTIONNAIRE DEVELOPMENT PHASES

A questionnaire was developed including 16 major causes that narrowed down from 51 causes for generating waste during construction from different resources including construction companies, professionals, educational institute, and literature review, to help identified the ones that occur in most projects.

B.2 A LIST OF COMMON CAUSES FOR WASTE GENERATION IN CONSTRUCTION PROJECTS ADDRESSED BY INDUSTRY, PROFESSORS OF PRACTICE, AND THE LITERATURE

Waste Source Category	Cause	References		
		Industry	Professors of practice	Literature
Labor	1. Untrained workers		✓	✓
	2. Errors by laborers	✓	✓	✓
	3. Lack of teamwork	✓	✓	✓
	4. Inexperienced designer	✓	✓	✓
	5. Lack of influence of contractors and lack of knowledge about construction			✓
	6. Contractor unfamiliarity with the project/site location			✓
	7. Poor fabrication			✓
Measures	8. Ordering errors (too much/too little)	✓	✓	✓
	9. Errors by suppliers	✓	✓	✓
	10. Lack of possibilities to order small quantities of materials	✓		✓
	11. Over mixing of materials for wet trades due to lack of knowledge of requirements			✓
	12. Designer is not familiar with possibility of different products			✓
	13. Offcuts from cutting materials to length	✓		✓
	14. Conversion waste from cutting uneconomical shapes			✓
	15. Poor Project Estimate	✓	✓	
Materials	16. Damages during transportation to site/onsite	✓	✓	✓
	17. Damages subsequent	✓	✓	✓
	18. Materials do not comply with specifications	✓	✓	✓
	19. Low quality materials			✓
	20. Having materials from whatever place that close to the site			✓
	21. Choices about specifications of products			✓
	22. Use of products that do not fit			✓
	23. Use of incorrect materials that need replacement			✓
	24. Poor materials preparation for concrete	✓		✓
	25. Difficulty controlling quantities for materials such as concrete	✓		
	26. Poor scheduling		✓	✓
	27. Delay of passing information to the contractor	✓	✓	✓

B.2 (CONTINUED)

Waste Source Category	Cause	References		
		Industry	Professors of practice	Literature
Method	28. Design changes during construction	✓	✓	✓
	29. Errors in contract documents	✓	✓	✓
	30. Inappropriate storage leading to damage	✓	✓	✓
	31. Contract documents are not complete at commencement of construction	✓		✓
	32. Method to lay foundation			✓
	33. Waste from application process			✓
	34. Complexity of detailing in the drawings			✓
	35. Complexity of the design	✓		✓
	36. Lack of information in the drawings			✓
	37. Unpacked supply			✓
	38. Lack of on-site control and management		✓	✓
	39. Materials placed in the wrong place on site			✓
	40. Lack of quality inspection		✓	✓
	41. Choosing qualified contractor during the bid process		✓	✓
Uncontrollable events	42. Bad weather	✓	✓	✓
	43. Unexpected injuries on construction site	✓	✓	✓
	44. Criminal waste due to damage or theft			✓
	45. Natural disaster			✓
	46. Lack of basic services near to project location			✓
Machines	47. Use of low quality tools	✓	✓	✓
	48. Use of sophisticated technology	✓	✓	✓
	49. Equipment malfunction		✓	✓
	50. Untrained equipment operators			✓
	51. Poor equipment maintenance		✓	✓

B.3 SAMPLES OF THE QUESTIONNAIRE FILLED OUT BY THE CONSTRUCTION CONSULTANT COMPANY

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

Please rank the following in order (1-16), 1 the highest, by whom you perceive generates the most, waste during construction.
Note: waste consists of materials, time, energy, money

Rank	Item
4	Errors by laborers
1	Design changes during construction is in process
5	Designers with less experience in methods and sequence of construction
10	Unfriendly attitudes of the project members
2	Delay in passing information to the contractor
7	Errors in contract documents
6	Bad weather
15	Unexpected injuries on construction site
8	Use of a sophisticated technology
9	Use of low quality tools and products
3	Ordering errors (too much or too little)
11	Errors by suppliers
14	Inappropriate storage leading to deterioration
12	Materials not in compliance with specifications
16	Damages subsequent
13	Damages during transportation
	Other, please specify:

Please rank the following in order (1-16), 1 the highest, by whom you perceive generates the most, waste during construction.
Note: waste consists of materials, time, energy, money

Rank	Item
2	Errors by laborers
1	Design changes during construction is in process
7	Designers with less experience in methods and sequence of construction
3	Unfriendly attitudes of the project members
16	Delay in passing information to the contractor
11	Errors in contract documents
4	Bad weather
5	Unexpected injuries on construction site
15	Use of a sophisticated technology
6	Use of low quality tools and products
8	Ordering errors (too much or too little)
12	Errors by suppliers
9	Inappropriate storage leading to deterioration
10	Materials not in compliance with specifications
13	Damages subsequent
15	Damages during transportation
	Other, please specify:

B.3 (CONTINUED)

Please rank the following in order (1-16), 1 the highest, by whom you perceive generates the most, waste during construction. Note: waste consists of materials, time, energy, money	
Rank	**Item**
[illegible]	Errors by laborers
1	Design changes during construction is in process
13	Designers with less experience in methods and sequence of construction
15	Unfriendly attitudes of the project members
[illegible]	Delay in passing information to the contractor
7	Errors in contract documents
11	Bad weather
14	Unexpected injuries on construction site
16	Use of a sophisticated technology
6	Use of low quality tools and products
[illegible]	Ordering errors (too much or too little)
[illegible]	Errors by suppliers
8	Inappropriate storage leading to deterioration
4	Materials not in compliance with specifications
9	Damages subsequent
12	Damages during transportation
	Other, please specify:

Please rank the following in order (1-16), 1 the highest, by whom you perceive generates the most, waste during construction. Note: waste consists of materials, time, energy, money	
Rank	**Item**
12	Errors by laborers
1	Design changes during construction is in process
6	Designers with less experience in methods and sequence of construction
15	Unfriendly attitudes of the project members
4	Delay in passing information to the contractor
2	Errors in contract documents
13	Bad weather
3	Unexpected injuries on construction site
16	Use of a sophisticated technology
11	Use of low quality tools and products
10	Ordering errors (too much or too little)
7	Errors by suppliers
14	Inappropriate storage leading to deterioration
5	Materials not in compliance with specifications
9	Damages subsequent
8	Damages during transportation
	Other, please specify:

B.3 (CONTINUED)

Please rank the following in order (1-16), 1 the highest, by whom you perceive generates the most, waste during construction. Note: waste consists of materials, time, energy, money	
Rank	**Item**
15	Errors by laborers
2	Design changes during construction is in process
4	Designers with less experience in methods and sequence of construction
5	Unfriendly attitudes of the project members
8	Delay in passing information to the contractor
1	Errors in contract documents
10	Bad weather
16	Unexpected injuries on construction site
9	Use of a sophisticated technology
6	Use of low quality tools and products
3	Ordering errors (too much or too little)
11	Errors by suppliers
12	Inappropriate storage leading to deterioration
7	Materials not in compliance with specifications
13	Damages subsequent
14	Damages during transportation
	Other, please specify:

Table B- 1 Rating system used to calculate factors causing the most construction waste based on the questionnaire

Survey No.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	6	12	3	1	1	1	1	1	1	1	1	1	1	1	1	1
2	3	12	1	1	6	1	1	1	1	1	1	1	1	1	1	1
3	12	6	1	1	1	1	1	1	1	1	1	1	1	1	1	3
4	3	12	1	1	1	1	1	1	1	1	1	1	1	1	6	1
5	1	12	1	1	6	1	1	3	1	1	1	1	1	1	1	1
6	6	3	1	1	12	1	1	1	1	1	1	1	1	1	1	1
7	6	1	3	1	12	1	1	1	1	1	1	1	1	1	1	1
8	1	6	1	1	12	1	1	1	1	1	1	1	3	1	1	1
9	6	12	1	3	1	1	1	1	1	1	1	1	1	1	1	1
10	3	12	1	1	1	1	1	1	1	1	1	1	1	1	6	1
11	3	12	1	1	1	1	1	1	1	1	1	1	1	1	1	6
12	3	12	1	1	6	1	1	1	1	1	1	1	1	1	1	1
13	1	12	1	1	3	1	1	1	1	1	6	1	1	1	1	1
14	1	6	1	1	12	1	1	1	1	1	1	1	1	3	1	1
15	1	6	1	1	3	1	1	1	1	1	12	1	1	1	1	1
16	1	12	1	6	1	1	1	1	1	1	1	1	1	1	1	1
17	1	3	1	1	12	1	1	1	1	1	1	1	1	1	6	1
18	3	6	1	1	12	1	1	1	1	1	1	1	1	1	1	1
19	6	12	1	1	1	1	3	1	1	1	1	1	1	1	1	1
20	12	3	1	1	1	1	1	1	1	1	1	1	6	1	1	1
21	1	12	1	1	1	6	1	1	1	1	3	1	1	1	1	1
22	1	3	1	1	6	1	1	1	1	1	1	1	1	1	1	12
23	1	6	1	1	3	1	1	1	1	1	1	1	1	1	12	1
24	1	6	1	1	3	1	1	1	1	1	1	1	1	1	12	1
25	1	3	1	1	12	1	1	1	1	1	1	6	1	1	1	1
26	1	12	1	1	6	1	1	1	1	1	3	1	1	1	1	1
27	3	12	1	1	6	1	1	1	1	1	1	1	1	1	1	1
28	6	1	12	1	3	1	1	1	1	1	1	1	1	1	1	1
29	1	6	1	1	1	12	1	1	1	1	3	1	1	1	1	1
30	1	12	1	1	6	1	1	1	1	1	1	1	1	1	3	1
Total	**96**	**245**	**50**	**32**	**152**	**46**	**32**	**34**	**30**	**30**	**52**	**35**	**37**	**32**	**69**	**48**

Scoring: 1^{st} = 12 points , 2^{nd} = 6 points , 3^{rd} = 3 points , 4^{th} – 16^{th} = 1 point

Key Legend:

A. Errors by laborers.
B. Design changes during construction.
C. Designers with less experience in methods and sequence of construction.
D. Unfriendly attitude of the project members.
E. Delay in passing information to the contractor.
F. Errors in contract documents.
G. Bad weather.
H. Unexpected injuries on construction site.
I. Use of sophisticated technology.
J. Use of low quality tools and products.
K. Ordering errors (too much or too little).
L. Errors by suppliers.
M. Inappropriate storage leading to deterioration.
N. Materials not in compliance with specifications.
O. Damage subsequent.
P. Damages during transportation.

B.4 CASE STUDY: DATA INPUT USED FOR THE PILE CAP PROCESS

- Total number of pile caps for the MSCI project was 17. Some pile caps were 8” × 8” thick and some were 6” x 4” thick.
- Required quantity and type of equipment used for the construction of the pile cap process was based on RS means (2009).
- Duration for equipment usage was taken from the contractor’s project scheduling information.
- Data for construction materials was from the final construction reports, which included both the estimated and the actual quantities.
- Transportation included a 28-ton truck to deliver the form materials and waste, and a 32-ton concrete truck to deliver the concrete (213 kilometer).
- The data input involved several types of equipment: the excavator, the concrete pump, and the concrete vibrator. The data sources for these pieces of equipment are from the process LCA.
- The amount of fuel used in gallons was determined by multiplying the actual working hours by horsepower by 0.04 for the diesel equipment and by multiplying actual hours by horsepower by 0.06 for the gasoline equipment (Peurifoy and Schexnayder 2002).

B.5 CASE STUDY: MATERIALS QUANTITIES FOR PILE CAP PROCESS

MCSI - Quantities Tracked					
				Quantity	
Division	**Category (If Applicable)**	**Cost Item**	**Unit**	**Estimated**	**Actual**
02 - Site Construction	General Conditions	Shoring / Scaffolding	SF	1334	1034
	Concrete Demolition	Demo SOG - Sub-Basement	SF	544	544
		Demo Slab - Basement	SF	939	400
		Demo Slab - Plaza	SF	1700	7910
		Demo - Salvage Planters / Stairs	LS	1	1
		Rework Pavers / Off-Site Storage	LS	1	1
	Demolition	Interior Demo - Sub & Basement		2500	2500
	Structural Excavation & Backfill	Interiors		227	120
		Exterior Pile Caps	LS	619	1
	Site Furnishings	Site Furnishings - Allowance	LS	1	1
03 - Concrete	General Conditions	Misc. Formwork and Lumber	LS	1	1
		Concrete Pump	Days	48	48
		Concrete Pump Slick Lines	MD	32	22
		Cranes (< 50 Tons)	Month	6	7
		Stone Subbase Material	LS	1	1
	Concrete Reinforcement	Reinforcing Steel	LS	1	1
		Misc. Reinforcing Materials	LS	1	1
	Pile Caps	Pour / F / C Pile Caps	CY	228	225
		Pile Cap Form		2428	1200
	Columns	Concrete (w/ waste)	CY	205	268.5
		A-Line Columns	SF	932	5526
		Basement & Sub-Basement Columns	SF	2703	2698
		K-Wall	SF	2350	1290
		Y-Column	SF	1188	736
		Typical Bldg Column	SF	5688	2088
		Rub Columns	SF	9323	9580
		Spray Cure	SF	9323	9323
	Concrete Walls - Handset	Handset	LS	1	1
		Concrete	CY	168.52	19
		Wall Forms > 8' High Curbs	SF	4550	2175
		Finish Top of Wall	SF	0	54
		Knock Fins & Patch	SF	4550	4550
		Rub Finish	SF	4550	4550

B.5 (CONTINUED)

MCSI - Quantities Tracked					
				Quantity	
Division	Category (If Applicable)	Cost Item	Unit	Estimated	Actual
	Sub-base for Slab Work	Stone Sub-base	Tons	348	350
		Fine Grade Stone Sub-base	SF	4700	4700
	Slab on Grade	Concrete	CY	128	86
		Edge Form	LF	1100	962
		Drill Dowels	Ea	840	473

APPENDIX C

C.1 CASE STUDY LOCATION: SAUDI ARABIA

Figure C- 1 Location for the three residential projects in MYAS

C.2 ADDITIONAL PHOTOS FOR RESIDENTIAL UNITS SHOWING PAINT BLISTERING AND PAINTING PROCESS EQUIPMENT

C.3 FINAL CHECK SHEET SHOWING MAJOR PAINTING BLISTERING CAUSES

PROJECT NAME: ROYAL COMMISSION PUBLIC HOUSING (PHASE 4)					
LOCATION: INDUSTRIAL YANBU, SAUDI ARABIA			HAII AL-FAISAL HARRAH 1 NUMBER OF TOTAL UNITS: 53		
Unit		Causes of Error (Blistering in Exterior Painting)			
		1- Workers - Preparation of Materials - Execution of Training	2- Method: Current Process: 1- Plastering 2-applying primer sealer 3- Applying Paint	3- Weather Conditions: - High Temperature - Humidity - Dust	4- Other - Structural (Cracks) - Plumbing
	1/30	×			
	2/30	×			
	3/30	×			
	4/30	×			
	5/30	×			
	6/30	×			
	7/30	✓			
	8/30	×			
	1/31	×			
	2/31	✓			
	3/31	✓			
	4/31	✓			
	5/31			×	
	6/31			×	
	7/31			×	
	8/31	×			
	9/31			×	
	10/31	✓			
	1/32	✓			
	2/32	✓			
	3/32	×			
	4/32		×		
	5/32		×		
	6/32	×			
	7/32			×	
	8/32			×	
	1/33		×		

C.3 (CONTINUED)

PROJECT NAME: ROYAL COMMISSION PUBLIC HOUSING (PHASE 4)				
LOCATION: INDUSTRIAL YANBU, SAUDI ARABIA			HAII AL-FAISAL HARRAH 1 NUMBER OF TOTAL UNITS: 53	
Unit	Causes of Error (Blistering in Exterior Painting)			
	1- Workers - Preparation of Materials - Execution of Training	- Method: Current Process: 1- Plastering 2-applying primer sealer 3- Applying Paint	- Weather Conditions: - High Temperature - Humidity - Dust	4- Other - Structural (Cracks) - Plumbing
2/33		×		
3/33		×		
4/33				×
5/33		×		
6/33		×		
7/33		×		
8/33		×		
9/33			×	
10/33			×	
11/33	×			
12/33	×			
13/33				×
15/33			✓	
17/33			✓	
1/34		×		
2/34		×		
3/34				×
4/34		×		
5/34		×		
6/34		×		
7/34		×		
8/34		×		
9/34		×		
10/34		×		
11/34			✓	
12/34			✓	
No. Of Defects	13	18	8	3
Total Number of Defects				42
Total Number of Checks				11
Total Number of checks/Opportunities for defects				53
Defective Per Million Opportunities (DPMO)				792,453
Six-Sigma level				1 out of 6

C.4 CASE STUDY: MODIFIED PROCESS INCLUDING THE TWO STEPS ADDED

POST-EVALUATION

Finishing works Exterior Painting	
Project Name: HOP Unit Number: xxxxxxx Unit Type:	Location: Haii Al-Faisal Harah 1 Date: Time:
Scope of work:	
Step 1: Pre-Plaster: To prevent any humidity reaching the outside surface from inside the building. **Comment:**	
Step 2:Plaster: 2.5 mm thickness. **Comment:**	
Step 3:Clean the outside surface: To remove dust or any other element which could lead to blistering in paint. **Comment:**	
Step 4:Apply primer sealer: for surface leveling (if applicable) **Comment:**	
Step 5:Apply paint: 2 coats **Comment:**	

C.5 CASE STUDY: MATERIAL QUANTITIES AND PRICES

TABLE P-2

SCHEDULE OF PRICES AND QUANTITIES

Pay Item (Ref to Section 01150)	Description	Unit	Estimated Quantity	Unit Price (SR.)	ESTIMATED AMOUNT (SR)
03.02.08.	Ceiling Finishes:				
03.02.08.01.A.	Cement Plaster	SM	29,600	20.90	618,640.00
03.02.08.01.B.	Cement Plaster	SM	11,200	20.90	234,080.00
03.02.08.01.C.	Cement Plaster	SM	15,600	20.90	326,040.00
03.02.08.01.D.	Cement Plaster	SM	3,600	20.90	75,240.00
03.02.08.02.A.	Suspended gypsum board	SM	2,590	61.50	159,285.00
03.02.08.02.B.	Suspended gypsum board	SM	980	61.50	60,270.00
03.02.08.02.C.	Suspended gypsum board	SM	1,768	61.50	108,732.00
03.02.08.02.D.	Suspended gypsum board	SM	408	61.50	25,092.00
03.02.09.	Paint Systems:				
03.02.09.01.A.	Paint on Exterior Concrete and Cement Plaster	SM	59,348	18.75	1,112,775.00
03.02.09.01.B.	Paint on Exterior Concrete and Cement Plaster	SM	23,352	18.75	437,850.00
03.02.09.01.C.	Paint on Exterior Concrete and Cement Plaster	SM	40,404	18.75	757,575.00
03.02.09.01.D.	Paint on Exterior Concrete and Cement Plaster	SM	11,184	18.75	209,700.00
03.02.09.02.A.	Paint on Interior Concrete and Cement Plaster	SM	79,180	16.85	1,334,183.00
03.02.09.02.B.	Paint on Interior Concrete and Cement Plaster	SM	29,960	16.85	504,826.00
03.02.09.02.C.	Paint on Interior Concrete and Cement Plaster	SM	42,640	16.85	718,484.00
03.02.09.02.D.	Paint on Interior Concrete and Cement Plaster	SM	9,840	16.85	165,804.00
03.02.09.03.A.	Paint on gypsum board	SM	2,590	18.00	46,620.00
03.02.09.03.B.	Paint on gypsum board	SM	980	18.00	17,640.00
03.02.09.03.C.	Paint on gypsum board	SM	1,768	18.00	31,824.00
03.02.09.03.D.	Paint on gypsum board	SM	408	18.00	7,344.00
03.02.10.	Wall Wooden Cabinet				
03.02.10.01.A.	600mm D x 2700mm W x2900mm H	EA	74	8,695.00	643,430.00
03.02.10.01.B.	600mm D x 2700mm W x2900mm H	EA	28	8,695.00	243,460.00
03.02.10.02.A.	400mm D x 1300mm W x2900mm H	EA	74	4,295.00	317,830.00
03.02.10.02.B.	400mm D x 1300mm W x2900mm H	EA	28	4,295.00	120,260.00
03.02.10.03.A.	600mm D x 1500mm W x2900mm H	EA	74	5,420.00	401,080.00
03.02.10.03.B.	600mm D x 1500mm W x2900mm H	EA	28	5,420.00	151,760.00
03.02.10.04.A.	800mm D x 1800mm W x2900mm H	EA	74	6,650.00	492,100.00
03.02.10.04.B.	800mm D x 1800mm W x2900mm H	EA	28	6,650.00	186,200.00
03.02.10.05.C.	600mm D x 1800mm W x2900mm H	EA	52	5,985.00	311,220.00
03.02.10.05.D.	600mm D x 1800mm W x2900mm H	EA	12	5,985.00	71,820.00
03.02.11.	Toilet Accessories:				
03.02.11.01.A.	Robe Hooks	EA	444	30.00	13,320.00
03.02.11.01.B.	Robe Hooks	EA	168	30.00	5,040.00

C.5 (CONTINUED)

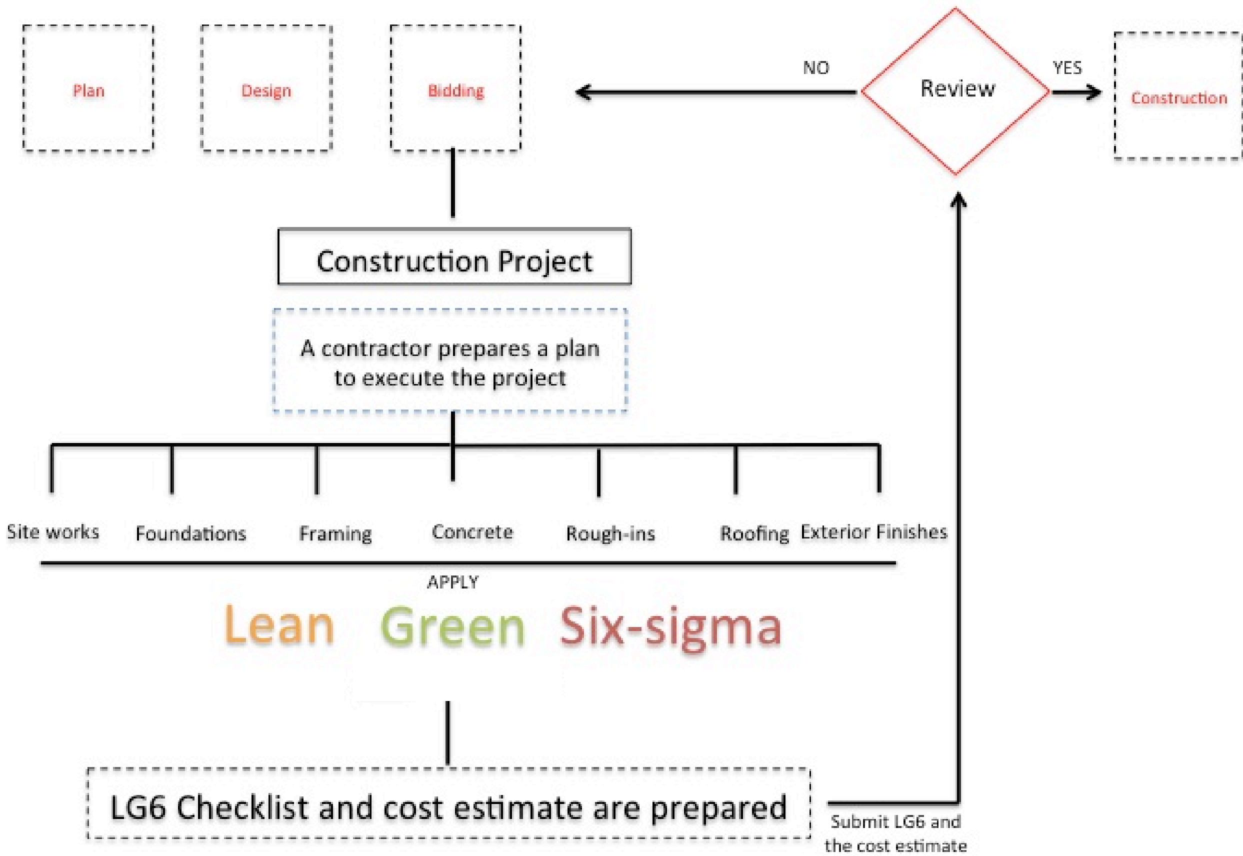
TABLE P-2

SCHEDULE OF PRICES AND QUANTITIES

Pay Item (Ref to Section 01150)	Description	Unit	Estimated Quantity	Unit Price (SR.)	ESTIMATED AMOUNT (SR)
03.02.05.06.C.	Terrazo tiles for terraces (Not Used)				
03.02.05.06.D.	Terrazo tiles for terraces (Not Used)				
03.02.05.07.A.	Marble base skirting 80x20mm thk.	LM	2,960	49.30	145,928.00
03.02.05.07.B.	Marble base skirting 80x20mm thk.	LM	1,120	49.30	55,216.00
03.02.05.07.C.	Marble base skirting 80x20mm thk.	LM	2,080	49.30	102,544.00
03.02.05.07.D.	Marble base skirting 80x20mm thk.	LM	480	49.30	23,664.00
03.02.06.	Wall Finishes & Accessories:				
03.02.06.01.A.	Exterior Cement Plaster	SM	54,168	22.60	1,224,196.80
03.02.06.01.B.	Exterior Cement Plaster	SM	23,352	22.60	527,755.20
03.02.06.01.C.	Exterior Cement Plaster	SM	36,764	22.60	830,866.40
03.02.06.01.D.	Exterior Cement Plaster	SM	10,104	22.60	228,350.40
03.02.06.02.A.	Interior Cement Plaster	SM	49,210	18.50	910,385.00
03.02.06.02.B.	Interior Cement Plaster	SM	18,760	18.50	347,060.00
03.02.06.02.C.	Interior Cement Plaster	SM	44,200	18.50	817,700.00
03.02.06.02.D.	Interior Cement Plaster	SM	10,320	18.50	190,920.00
03.02.06.03.A.	Ceramic Tiles	SM	20,794	65.00	1,351,610.00
03.02.06.03.B.	Ceramic Tiles	SM	8,008	65.00	520,520.00
03.02.06.03.C.	Ceramic Tiles	SM	10,400	65.00	676,000.00
03.02.06.03.D.	Ceramic Tiles	SM	2,400	65.00	156,000.00
03.02.06.04.A.	GRC decorative element on villa exterior	EA	518	367.00	190,106.00
03.02.06.04.B.	GRC decorative element on villa exterior	EA	252	367.00	92,484.00
03.02.06.04.C.	GRC decorative element on villa exterior	EA	468	367.00	171,756.00
03.02.06.04.D.	GRC decorative element on villa exterior	EA	132	367.00	48,444.00
03.02.06.05.A.	GRC 60 cm height decorative skirting around villa exterior	LM	4,255	332.50	1,414,787.50
03.02.06.05.B.	GRC 60 cm height decorative skirting around villa exterior	LM	1,960	332.50	651,700.00
03.02.06.05.C.	GRC 60 cm height decorative skirting around villa exterior	LM	2,418	332.50	803,985.00
03.02.06.05.D.	GRC 60 cm height decorative skirting around villa exterior	LM	732	332.50	243,390.00
03.02.06.06.A.	Ceramic tiles on exterior elevations	SM	1,036	68.00	70,448.00
03.02.06.06.B.	Ceramic tiles on exterior elevations	SM	462	68.00	31,416.00
03.02.06.06.C.	Ceramic tiles on exterior elevations	SM	499	68.00	33,932.00
03.02.06.06.D.	Ceramic tiles on exterior elevations	SM	144	68.00	9,792.00
03.02.07.	Wall Bases:				
03.02.07.01.A.	Ceramic Tiles	LM	25,160	16.75	421,430.00
03.02.07.01.B.	Ceramic Tiles	LM	9,520	16.75	159,460.00
03.02.07.01.C.	Ceramic Tiles	LM	18,980	16.75	317,915.00
03.02.07.01.D.	Ceramic Tiles	LM	4,440	16.75	74,370.00

APPENDIX D

D.1 APPLYING LG6 IN PRE-CONSTRUCTION PHASE



D.2 CONSTRUCTION MATERIALS AND ASSOCIATED ENVIRONMENTAL IMPACTS IN THE LG6 MODEL

To help the user calculate environmental impact, the LG6 model provides a summary of the characterization factors for associated environmental impacts for the most common materials used in construction, such as concrete, steel, blocks, etc. Using values generated in the SimaPro7 software, these characterization factors represent the magnitude of impact per single unit in each specific impact category. For example, the global warming potential of steel is 1.049 grams of CO2 equivalent per kilogram of steel used, and the Acidification potential is 0.517 grams of H+ moles equivalent per kilogram of steel used. This conversion process allows the aggregation of impacts from every step in the process, resulting in a single value for the overall process in each environmental impact category.

The environmental impacts generated during the construction phase

Impact Categories	Global Warming	Acidification	Carcinogenics	Non carcinogenics	Respiratory effects	Eutrophication	Ozone depletion	Eco toxicity	Smog
	kg CO2 eq	H+ moles eq	kg benzen eq	kg toluen eq	kg PM2.5 eq	kg N eq	kg CFC-11 eq	kg 2,4-D eq	kg NOx eq
Unit Process									
Fuel									
Gasoline fuel oil/ 1gal	1.89616635	1.30675851	0.00459386	96.910346	0.00200482	0.00089055	5.2967E-10	2.69123668	0.01283942
Diesel/1gal	1.74214949	1.20061653	0.00422073	89.0387651	0.00184198	0.00081821	4.8665E-10	2.47263992	0.01179653
Materials									
Steel									
Steel/1kg	1.04968225	0.51784908	0.03093768	54.9398648	0.00190566	0.00026251	3.5131E-09	0.12358152	0.00512283
Wood									
Wood/1 lf	-0.8778358	0.08816877	0.00012689	0.58933964	0.00030269	5.1072E-05	2.3375E-12	0.01224021	0.00111946
Binders									
Adhesive mortar, at plant-1kg	1.10053548	0.25319214	0.00314864	41.9939511	0.00125802	0.00175761	2.8067E-07	1.50339662	0.00314088
Cement mortar, at plant-1kg	0.19505767	0.01945142	0.00016104	0.87548478	8.5587E-05	3.4674E-05	8.1025E-09	0.11070103	0.00031498
Lime mortar, at plant-1kg	0.61021125	0.05388511	0.00041037	1.65743413	0.00024553	7.3991E-05	2.0965E-08	0.19467788	0.00089007
Portland cement, strength class Z 42	0.834965	0.07183993	0.00054525	1.56823003	0.00031813	8.1727E-05	2.3115E-08	0.15311977	0.00119477
Bitumen									
Bitumen, at refinerY-1kg	0.42653427	0.25718833	0.00057734	6.5436072	0.00120832	0.0015574	4.4126E-07	0.35411814	0.00164948
Bricks									
Brick, at plant-1kg	0.21975242	0.03354792	9.826E-05	0.61099351	0.00013558	4.1883E-05	1.7823E-08	0.08511594	0.00050248
Ceramics I-1kg	0.21012189	0.04716878	1.8796E-07	0.00367088	0.00012001	2.8259E-05	8.3876E-12	0.00013322	0.00065758
Sand-lime brick, at plant-1kg	0.06401367	0.0119069	0.00014004	0.96814238	7.3204E-05	2.6438E-05	1.1713E-08	0.08398165	0.00015818
Cladding									
Cladding, crossbar-pole, aluminium-	150.370506	45.0614507	0.59959428	3309.35141	0.31882469	0.11469971	1.5245E-05	621.091701	0.38446793
Concrete									
Concrete block, at plant-1kg	0.1238159	0.01526665	0.00020287	0.7571039	7.7419E-05	2.6039E-05	4.4577E-09	0.06200464	0.00024787
Concrete, normal, at plant-1 m3	266.596917	27.7414346	0.24448419	1009.71987	0.12265623	0.03733933	8.8082E-06	71.188579	0.47342656
Concrete, sole plate and foundation,	163.06437	20.4814292	0.19882973	923.758137	0.09109056	0.03164733	7.0054E-06	58.7542448	0.34365701
Concrete (reinforced) I - 1kg	0.10865584	0.03971377	0.00125813	2.60040957	0.00014514	2.6192E-05	1.0609E-09	0.01955456	0.00043469
Covering									
Acrylic filler, at plant- 1kg	0.40810673	0.09847809	0.00097496	8.05964019	0.00049422	0.00031957	4.2533E-08	0.49806026	0.00099592
Base plaster, at plant- 1kg	0.21765142	0.02109279	0.00016699	0.9220918	9.3994E-05	3.7175E-05	9.5522E-09	0.11835136	0.00034292
Cement cast plaster floor, at plant- 1	0.17474643	0.01969294	0.00018923	0.90226376	8.5615E-05	3.49E-05	6.4316E-09	0.1128415	0.00033773
Ceramic tiles, at regional storage- 1k	0.81574468	0.15290588	0.0028396	12.8020998	0.00961487	0.00030049	9.3027E-08	1.18344786	0.00136499
Clay plaster, at plant- 1kg	0.01873898	0.00387883	1.6197E-05	0.16357307	1.5638E-05	8.297E-06	2.6704E-09	0.01363536	6.353E-05
Concrete roof tile, at plant- 1kg	0.21177855	0.02631873	0.00030248	1.32221427	0.00014146	9.1158E-05	1.0338E-08	0.1112615	0.0003788
Cover coat, mineral, at plant- 1kg	0.08184319	0.01210511	7.9199E-05	0.83102055	0.00070369	2.1861E-05	1.1011E-08	0.16001855	0.00015972
Cover coat, organic, at plant- 1kg	0.18737575	0.03737056	0.00052763	4.72097141	0.00020118	9.2444E-05	1.7386E-08	0.20954761	0.00044166
Fibre cement corrugated slab, at pla	0.65100283	0.09142705	0.00203327	7.30065576	0.00055233	0.00024388	3.3894E-08	0.70203246	0.00127884
Fibre cement facing tile, at plant-1kg	0.81903179	0.11286889	0.00232166	8.78498326	0.00064764	0.00031624	4.7208E-08	0.87286272	0.00156441
Fibre cement roof slate, at plant-1kg	0.722304	0.10001448	0.00211755	7.8144732	0.00059274	0.00029262	4.2051E-08	0.78287522	0.00137829
Gypsum fibre board, at plant-1kg	0.29123115	0.05469887	0.00021438	2.6555154	0.00083693	0.00015087	3.5165E-08	0.3335374	0.00086033
Gypsum plaster board, at plant-1kg	0.35035777	0.06407846	0.00031907	4.16764068	0.00097325	0.00019412	4.0469E-08	0.41970686	0.00092669
Roof tile, at plant-1kg	0.35686928	0.05356195	0.00012644	0.83615395	0.00019882	5.6508E-05	2.6255E-08	0.1319622	0.00070365
Thermal plaster, at plant-1kg	0.77454738	0.0875136	0.00059557	6.35585791	0.00039346	0.00013789	2.6108E-08	0.32716539	0.00140735
Doors									
Door, inner, glass-wood, at plant- 1n	-13.205043	14.6430549	0.13604867	1117.97701	0.08139558	0.03263783	4.0374E-06	121.256345	0.16413701
Door, inner, wood, at plant- 1m2	-38.002386	9.75652351	0.08730333	865.159708	0.05924095	0.03122703	3.2656E-06	88.6615182	0.12029134
Door, outer, wood-aluminium, at pla	49.8326537	32.2832321	0.44011642	3149.63042	0.15379392	0.06794361	6.0205E-06	374.615419	0.20991023
Door, outer, wood-glass, at plant-1m	62.891339	35.0860166	0.46121011	3314.3007	0.15981653	0.0681582	6.3173E-06	337.94346	0.23517541
Cellulose fibre, inclusive blowing in,	0.28088716	0.14623291	0.00161019	31.6966392	0.00106722	0.00021251	4.0291E-08	1.06671574	0.00123806
Cork slab, at plant/RER S	-0.6532039	0.29776299	0.00235226	13.8337406	0.00174292	0.0005288	1.0306E-07	2.07426911	0.00360068
Foam glass, at plant/RER S	1.57800484	0.23095768	0.00154868	17.1795691	0.001103	0.00038534	1.7388E-07	8.53446997	0.00326905
Foam glass, at regional storage-	1.20384602	0.19548648	0.00138049	13.6026818	0.00075537	0.00040395	1.5781E-07	8.33269793	0.00340638
Glass wool mat, at plant/CH S	1.49607674	0.36547541	0.00501231	66.7785601	0.00131497	0.00112022	2.3151E-07	10.0839255	0.00361561
Mineral wool ETH S	1.59096136	0.49165923	0.00199477	42.4010793	8.7648E-05	0.00039966	5.2781E-07	1.41479374	0.00332644
Polystyrene foam slab, at plant-	4.14126148	0.75212594	0.00420662	98.8248655	0.00332479	0.00135964	1.3071E-07	2.89842863	0.01166799
Polystyrene, extruded (XPS), at plant	9.87558551	0.7652314	0.00569659	91.2388565	0.0035371	0.00131688	0.00017794	2.895905	0.00613781
Rock wool, at plant/CH S	1.45970991	0.44812538	0.00226839	8.46041366	0.0058432	0.00058486	6.4565E-08	1.20371635	0.00380301
Tube insulation, elastomere, at plant	4.42574307	1.42708222	0.02136715	433.915222	0.00738538	0.00263488	7.3956E-07	5.71433629	0.0090042
Urea formaldehyde foam slab, hard,	2.98177422	0.69048649	0.00835791	32.2369727	0.00362266	0.00355254	4.1377E-07	2.58320303	0.00669317
Anhydrite floor, at plant/CH S	0.04443346	0.0091432	8.2561E-05	0.74114571	0.00024024	2.5353E-05	5.5071E-09	0.1145711	0.0001253
Cobwork, at plant/CH S	-0.2057978	0.0011247	3.86E-06	0.04288963	5.5511E-06	1.768E-06	3.004E-10	0.007287	1.8209E-05
Mastic asphalt, at plant/CH S	0.20916186	0.03405375	9.8422E-05	1.0589709	0.00014855	9.0892E-05	8.1611E-08	0.1367836	0.00049215
Natural stone plate, cut, at regional stor	0.26257728	0.1084268	0.00022903	2.30094317	0.00048821	0.000188	3.518E-08	0.16428089	0.00224697
Natural stone plate, grounded, at region	0.35793653	0.14649164	0.00032378	3.30617016	0.00072334	0.00025314	4.7376E-08	0.23489835	0.00301707
Natural stone plate, polished, at regiona	0.43503194	0.17701045	0.00040271	4.15272444	0.0023082	0.0003052	5.7121E-08	0.29417355	0.00383067
Quarry tile, at plant/CH S	0.23071425	0.0255725	0.00027231	0.9609425	0.00012024	3.8607E-05	7.9147E-09	0.07983181	0.00042743
Alkyd paint, white, 60% in solvent, at pl	2.67543737	1.00990009	0.00658207	43.0473109	0.00456661	0.00903177	5.6737E-07	4.15160919	0.00798097
Paint ETH S	1.78668917	0.65406224	0.14750769	415.252234	0.00013831	0.00022533	1.2031E-06	1.37507918	0.00340017
Bitumen adhesive compound, cold, at p	0.39536745	0.14483674	0.00068121	5.18715599	0.00070149	0.00080566	1.9071E-07	0.40479905	0.00111617
Bitumen adhesive compound, hot, at pl	0.56776509	0.27341994	0.00079075	7.17038729	0.00128178	0.00160712	4.6111E-07	0.41798195	0.00189069
Natural rubber based sealing, at plant/D	1.93017629	0.4876783	0.00466753	23.2492751	0.00244282	0.00229422	4.229E-07	1.78170875	0.00438078
Polysulphide, sealing compound, at pla	1.55984633	0.46961636	0.00459901	42.3306696	0.00269604	0.0019358	1.2133E-07	2.37607357	0.00341311
Ventilation system, central, 1 x 720 r	7394.52793	4275.69935	60.2015854	398265.901	11.9288091	7.17428186	0.00041202	35668.3807	14.4388571
Ventilation system, decentralized, 6	8933.02228	4765.05668	74.2174622	447946.422	14.4756923	8.33480126	0.00052924	57035.345	17.437644
Ventilation system, central, 1 x 720 r	11350.4686	10573.8465	129.830174	1053623.74	23.3537397	15.3351606	0.00083261	61071.3066	25.9468278
Ventilation system, decentralized, 6	4647.06502	2526.0698	47.6373047	317826.213	8.21617332	4.61182392	0.00032001	46356.1771	9.30609505
Ventilation system, decentralized, 6	12888.6604	11062.9968	143.843903	1103289.88	25.9006101	16.4955954	0.00094979	82436.3283	28.9441607
Ventilation system, decentralized, 6	8602.73436	8824.14422	117.265476	973180.394	19.6408577	12.7727218	0.00074058	71758.3642	20.8127518
Window frame, aluminium, U=1.6 W	476.338176	106.352601	1.38080188	6267.91047	0.77052278	0.29919644	3.5491E-05	2629.90355	0.84358778
Window frame, plastic (PVC), U=1.6	254.89144	81.9532115	4.44033089	11681.1063	0.40549077	0.18599524	1.1364E-05	613.625282	0.63122797
Window frame, wood-metal, U=1.6 '	85.9601883	61.3100204	2.05100923	45526.5355	0.40628788	0.16328439	1.7688E-05	1160.59951	0.57530901
Window frame, wood, U=1.5 W/m2I	-39.676457	37.2466943	0.57691069	6733.26384	0.22975369	0.10136596	1.0531E-05	468.551714	0.39802064

Figure D- 1 Construction materials in LG6 model and associated environmental impacts using TRACI

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