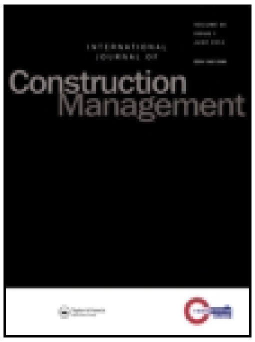

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A framework to improve construction processes: Integrating Lean, Green and Six Sigma

Abdulaziz Banawi and Melissa M. Bilec*

Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA

The construction industry consumes a significant amount of resources annually, generates significant waste and produces a host of emissions. This study 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 was 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 impact arising from waste, and analyzes the root causes behind waste generation to enable improved process performance. A survey of construction professionals regarding the causal factors of waste in everyday construction activities identified 'design changes during construction' as responsible for 60% of waste occurrences during construction and thus confirm results from the literature. In conclusion, the Lean–Green–Six Sigma framework offers a comprehensive, multi-stage approach for process improvement and minimization of life cycle environmental impacts.

Keywords: construction industry; construction processes improvement; value stream mapping; Six Sigma; life cycle assessment; greening construction processes

Introduction

The construction industry contributed over US$558 billion to the United States' gross domestic product (GDP) in 2012 (U.S. Department of Commerce 2012) and employed over seven million workers during that time (U.S. Census Bureau 2012). This industry consumes vast quantities of resources and energy and produces an abundance of waste. In the United States, every year about 160 million tons of the solid waste entering landfills is from construction activities alone (U.S. Environmental Protection Agency 2009a). Resources, energy, and cost can be 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 & Zawislak 2005; Garrett & Lee 2011), minimize environmental impacts (Bilec et al. 2006, 2010) or increase productivity (Pheng & Hui 2004; Celep et al. 2012), to date there has been limited research on how to combine and achieve all three. This study integrates three methods: **Lean** to reduce waste, **Green** to assess the environmental impact and **Six Sigma** to improve productivity). It is based on the hypothesis that using these three methods together will help minimize impacts generated by construction activities and at the same time also improve efficiency and safeguard the bottom line.

Why Lean, Green and Six Sigma?

Lean, Green, and Six Sigma are complementary; therefore, each method has the potential to minimize the disadvantages of the others. Lean is valued for its ability to identify waste (Lapinski et al. 2006; Klotz et al. 2007), but it does not quantify environmental consequences. So, our aim was to consider Green to fill the gap and evaluate the impact of the generated waste (Guggemos & Horvath 2005; Sharrard et al. 2008; Li et al. 2010). Together, Lean and Green have the ability to identify waste and evaluate its environmental impact, but they often do not provide an actual method to reduce waste. Six Sigma has the potential to fill this gap (Han et al. 2008).

Lean is a business strategy with the primary objective of minimizing waste, with waste defined as anything that does not add value. Taiiachi Ohno, the father of the Toyota Production System, identified seven different forms of waste (Ohno 1990):

- **Transport –** Moving products or materials around. The more things move, the more chance there is for damage to occur.
- **Waiting –** Waiting in any form.
- **Overproduction –** Producing more than what the customer needs. Overproduction results in unnecessary inventory cost, materials consumption and manpower.

*Corresponding author. Email: mbilec@pitt.edu

- **Defect –** Any process that fails to transfer inputs to desired outputs.
- **Inventory –** Any inventory is considered a non-value added commodity, even though it may be needed. It is at risk of damage, obsolescence, spoilage and quality issues.
- **Motion –** Any physical movement by people that does not add value to the process.
- **Extra processing –** Any processing that does not add value to the product.

The Lean method offers different tools to help identify each of the seven aforementioned types of waste. This research applies value stream mapping (VSM), which is a Lean tool that creates a process flow diagram of materials and information. The VSM uses a systematic approach, covering all activities required to bring the product or service to completion, and showing all steps, highlighting any ineffectiveness in the value stream. It includes the following elements:

- **Process steps –** The VSM depicts each of the process steps in the value stream, including both value added and non-value added. It reveals process statistics, including cycle time, number of operators and quantity of inventory.
- **Inventory –** The VSM highlights the storage and the quantity and movement of inventory within the process.
- **Information flow –** The VSM depicts all supporting information required by the process, including schedule, specifications and orders.
- **Cycle time (CT) –** This includes the time required to complete one cycle of operation or one step in the process.
- **Work in process (WIP) –** This includes the condition of all intermediate products, which are neither raw materials nor final products (Sayer & Williams 2007).

Although Lean has the potential to identify the waste in the process, it does not quantify the environmental impacts of the process. However, life cycle assessment (LCA), which represents the Green method, can be used to evaluate environmental impacts.

LCA quantifies the environmental impacts of a product, process or service through its entire life cycle, starting from extraction material and energy used in the production process to acquisition, to product use and finally to disposal. The International Standardization Organization (ISO) and the American National Standards Institute (ANSI) have worked together to standardize LCA. The LCA is a four-step approach including goal and scope definitions, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation (American National Standards Institute 2006; International Organization for Standardization 2006). It is a valuable approach that helps in decision-making and creating opportunities for improvements within processes, such as construction for better environmental performance (Guggemos & Horvath 2005; Bilec et al. 2006; Sharrard et al. 2008; Li et al. 2010).

The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) is an impact assessment method developed by the U.S. Environmental Protection Agency (EPA). TRACI translates the environmental loads identified by the LCI into different categories, namely, ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, eco toxicity, human health criteria–related effects, human health cancer effects, human health non-cancer effects, fossil fuel depletion and land use effects (U.S. Environmental Protection Agency 2010).

While Lean is used to address the effects of waste in the process and Green via LCA can describe the waste's environmental impacts, together Lean and Green do not eliminate or reduce waste itself. This is the reason why Six Sigma is proposed as a third, complementary technique directed to eliminate waste.

Six Sigma is a comprehensive improvement method used to help businesses achieve and sustain a healthy level of success. The Six Sigma system focuses on customer needs, data, statistical analysis, continuous improvement and reinventing business. Sigma refers to the amount of inconsistency or variance occurring in the process, and Six Sigma equates in statistics to 3.4 defects per millions opportunities (DPMO). Six Sigma was introduced for the first time by Motorola and GE in the 1980s as a new management tool to help both companies. Motorola was searching for a solution to stay in business, while GE was trying to return to its former status after its decline. The status of both the companies changed after applying Six Sigma to their operations. By the end of 1998, GE had accumulated US$750 million in total sales, which grew to US$1.5 billion by the end of 1999. Motorola also accumulated saving (based on Six Sigma efforts) from 1987 to 1997 totalling US$14 billion. Since then many companies have adopted Six Sigma as part of their management procedures (Pande et al. 2000).

The Six Sigma method has many benefits, including identifying and eliminating sources of variation, extending success, setting performance goals for all parties, enhancing value to customers and executing strategic change. DMAIC is a Six Sigma five-phase improvement model: define, measure, analyze, improve, control. A number of tools and methods can be used in each of the five steps (see Table 1).

In this study, two Six Sigma tools were used: the cause–effect diagram and the Pareto chart. Selected for their ability to analyze and improve the processes, these tools are used to identify the source causing waste and variations in the process.

Table 1. Examples of tools and methods used in DMAIC (define, measure, analyze, improve, control) model.

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 and effect diagram • Continual improvement • Experiment
Improve: Act on the data to change the process for improvement	• Pareto chart • Failure mode and effects analysis (FMEA) • Process improvement • Variation reduction
Control: Monitor the process to sustain the gain	• Management commitment • Control plan • Process behavior chart

The cause and effect diagram, also known as a Fishbone or Ishikawa diagram, is used as a categorical brainstorming tool to determine the root cause hypothesis and the potential causes (the bones of the fish) for a specific effect (the head of the fish) (Pande et al. 2000).

The Pareto chart follows 80/20 rule based on Vilfredo Pareto's research findings that few (20%) vital causes have a greater impact than do many (80%) trivial causes, which in total have a lesser impact. The Pareto chart is a quality tool based on the Pareto principle, using attribute data with columns arranged in descending order, with highest occurrences shown first, while using a cumulative line to track the percentage of each category, enabling one to distinguish the 20% of items causing 80% of the problem (Munro et al. 2008).

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

- Identify waste at different stages in the construction process via VSM (i.e., the Lean tool).
- Quantify the environmental impacts of the waste via LCA.
- Eliminate or reduce the sources of waste via Six Sigma tools.

Methodology

A framework was developed combining the three methods, Lean, Green and Six Sigma, to improve the construction processes. To validate the framework, a case study approach was applied to the proposed framework to improve a single construction process in a project for an institutional facility. The framework required additional validation through a questionnaire that was developed by applying purposive sampling approach (Tongco 2007). The next section further elaborates on the research method.

Proposed framework

The overall framework structure is based on Six Sigma's DMAIC. The designed DMAIC's framework consists of three steps as illustrated in Figure 1.

- **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 one or more appropriate Six Sigma tools is selected and applied 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 applied 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.

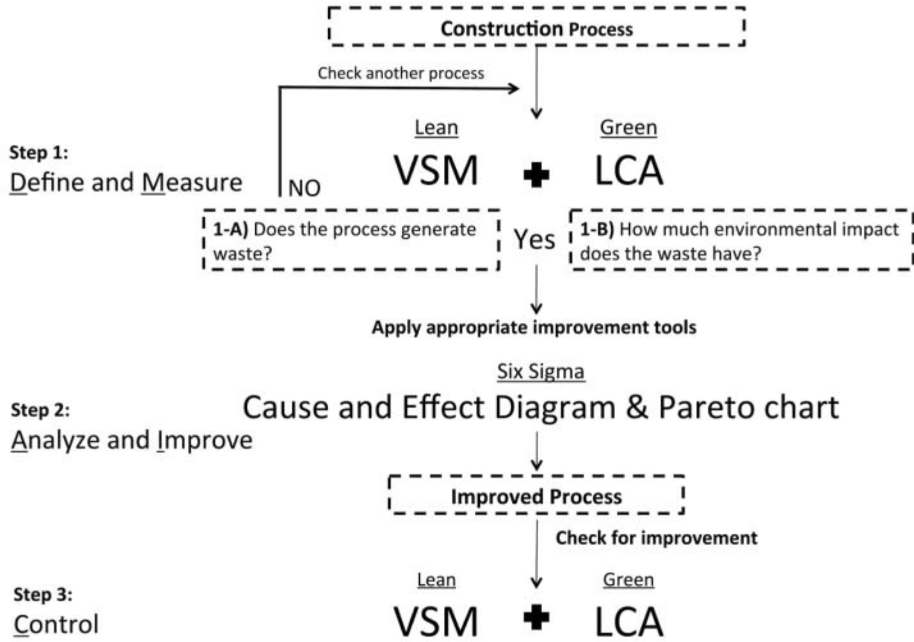

Figure 1. Lean, Green and Six Sigma framework.

Each step is further illustrated in the following case study.

Case study

A case study was developed to illustrate the functionality of the proposed 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 US$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 installing, (3) forming the pile caps and (4) placing and finishing the concrete.

Results and discussion

For Step 1-A, VSM was developed in order to identify, for each step of the pile cap process, where waste may occur; in addition, the VSM helped to explain the actual process and how the components interact with each other (see Figure 2). The VSM organizes four major elements: (1) project management, (2) installation of the pile cap process, (3) supplier and (4) customer. It systematically illustrates the relationships between the actors, data flow and logistics. 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. The cycle time (C/T) and delay time are illustrated on the timeline.

The data table for VSM revealed two issues: first, two different estimates were prepared for the quantity of materials required for the pile cap process (estimated/actual). For example, the estimated quantity for the forming materials was about 2428 sq. ft., while the actual quantity consumed was 1200 sq. ft. It is important to note that the estimated quantity reported in the documents is not necessarily proof that this quantity has been purchased and brought to the project. Both quantities in this study (estimated and actual) are included and evaluated by LCA to understand how environmental impact could increase along with the increase in the material quantities. Second, delays occurred between the pile cap installation phases (totalling 23 of the 54 total days). These delays impact both the owner and the contractor. Delay not only has economic consequences but also has the potential to increase environmental impacts due to the extra working hours and additional equipment use required to meet the project schedule.

For Step 1-B, LCA (Green) was used to evaluate the environmental impacts of the pile cap process. The LCA system boundary for the pile cap process includes raw materials extraction and manufacturing, transportation of equipment and

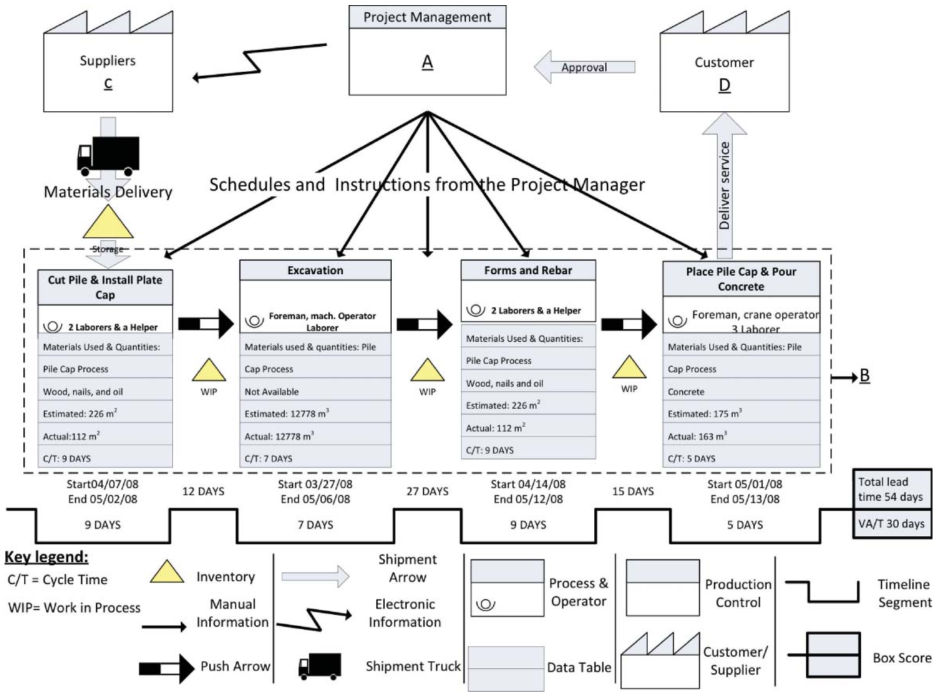

Figure 2. Value stream map (VSM) of the pile caps process.
Note: VSM is Step 1-A from Figure 1.

materials to the site 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 the change in activity duration due to delays specifically from 31 to 54 days. TRACI 2 V3.01 was used to perform the LCIA.

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

The comparative LCA results of the pile cap process for nine TRACI environmental impact categories are shown in Figure 3 for each of the 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 the final contractor reports. Of the general environmental impacts, material use exhibits 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 by waste. Transportation showed the least environmental impacts. A more specific analysis of each aspect follows.

Materials account for the highest impact in terms of global warming, carcinogenic, respiratory effects, ozone depletion and eco toxicity. Cement manufacturing is a significant contributor to environmental impact from materials.

Equipment manufacturing and combustion contributed the highest environmental impacts in two categories: acidification potential and smog potential. Moreover, equipment contributed the highest after materials in terms of global warming potential and respiratory effects. Diesel combustion is a notable contributor to respiratory effects (particulate matter $PM_{2.5}$), which can lead to issues related to respiratory system, including asthma and lung cancer (U.S. Environmental Protection Agency 2011).

Although the quantity of material waste generated in comparison to the actual materials utilized, seems insignificant, the environmental impact is substantial. The waste generation has the highest environmental impact on non-carcinogenic potential and on eutrophication potential; the additional waste, however, has more environmental impact than transportation.

While the concrete delivery was the most significant of the transportation processes, totalling 3642 ton km (see Table 2), the materials transportation generated the lowest environmental impacts.

For Step 2, the Six Sigma process improvement method was implemented using cause and effect diagram to analyze the root causes of the generated waste (Figure 4). Then a Pareto chart was used to explore how to improve the most commonly occurring waste causes. The cause and effect diagram helped identify the root causes of waste under several categories: uncontrollable events, materials, labor, machines, methods and measure. Out of 30 possible factors considered as possible causes of waste, only 16 are included on the cause and effect diagram. These 16 factors were chosen based on two

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

Construction-related activity					
	Ton km				
Transportation	**Estimated**	**Actual**	Remarks	Data sources	References
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	(Frishknecht et al. 2005)
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	(Frishknecht et al. 2005)
Equipment	**Fuel usage**				
	Estimated	**Actual**			
Excavation, hydraulic digger/RER S	1059 L	1059 L	Included processes: Includes the inputs 'hydraulic digger' for infrastructure, lubricating oil and fuel consumption, and some measured air emissions as output.	Ecoinvent system process	(Frishknecht et al. 2005)
Concrete pump, diesel equipment 406 HP	2450 L	2450 L	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 1990s.	Franklin USA 98	(Franklin Assoc. 1998)
Concrete vibrator, gasoline equipment 1.6 HP	38 L	16 L	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 1990s.	Franklin USA 98	(Franklin Assoc. 1998)
Concrete saw, gasoline equipment 5.6 HP	273 L	72 L	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 1990s.	Franklin USA 98	(Franklin Assoc. 1998)

(continued)

Table 2. (*Continued*)

Construction-related activity					
Materials	**Material usage**				
	Estimated	**Actual**			
Concrete, sole plate and foundation, at plant/CHS	175 m^3	163 m^3	Included processes: 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	226 m^2	112 m^2	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/CHS			This record should be used only with Ecoinvent data	Ecoinvent system process	(Frishknecht et al. 2005)
Concrete, sole plate and foundation, at plant/CHS	9 m^3		Included processes: 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	(Frishknecht et al. 2005)
Plywood, at plywood plant, US PNW/kg/US	56 m^2		Included processes: Final trim and saw to length of plywood. Base process data presented with allocations to within process co-products noted.	ecoinvent system processes	(Frishknecht et al. 2005)

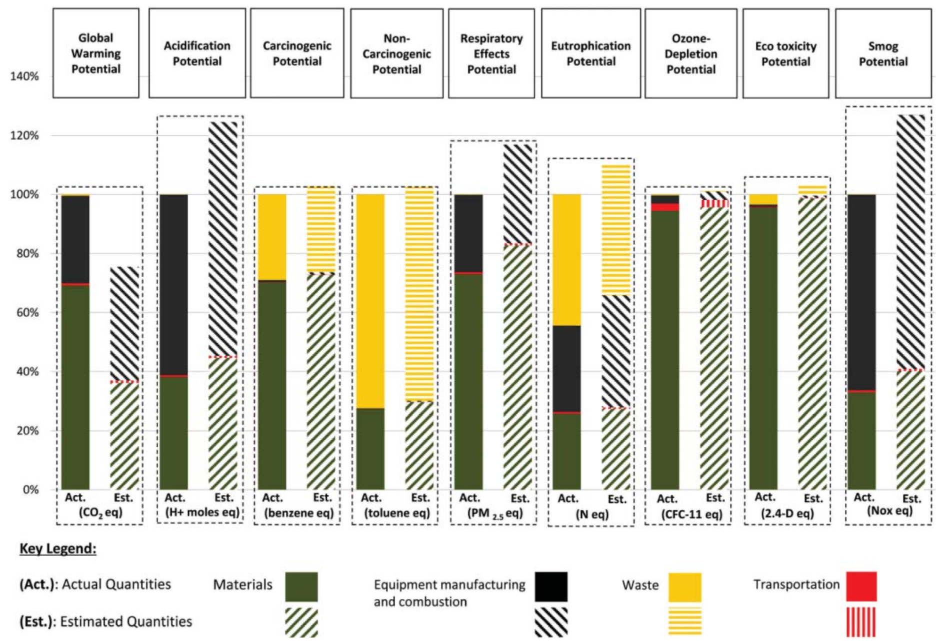

Figure 3. Life cycle environmental impacts of the pile cap process.
Note: Results are normalized to actual materials in Figure 3.

criteria: (1) the variables are independent and (2) the factors have been researched extensively in the literature (Bossink & Brouwers 1996; Formoso et al. 2002; Poon et al. 2004; Tam 2008). Independence here means that the occurrence of one cause of error does not affect the possibility that another cause of 16 causes will occur. For example, having inexperienced workers could lead to errors by labourers, while on the other hand damage during transportation could not lead to having materials that do not comply with specifications.

The set of 16 potential causal factors was further narrowed down to identify which factors contribute most to waste generation via a two-step process: a questionnaire was developed and sent to a construction claims consultant who then distributed it to 30 employees involved with daily on-site construction activities. All 30 responses were returned within 3 days. Using the purposive sampling approach, participants were pre-selected on the basis of their work experience at a

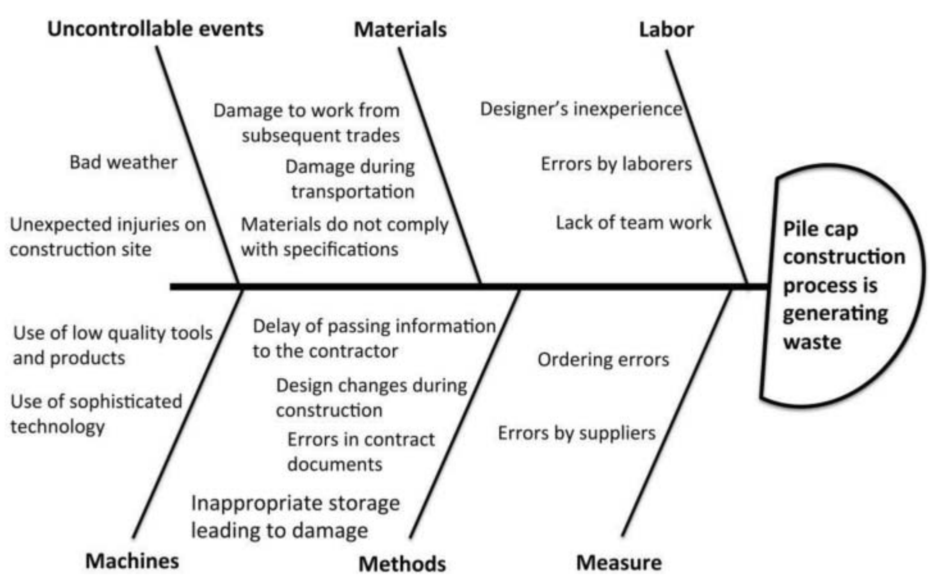

Figure 4. Cause and effect diagram: Common factors causing waste in the pile cap process.

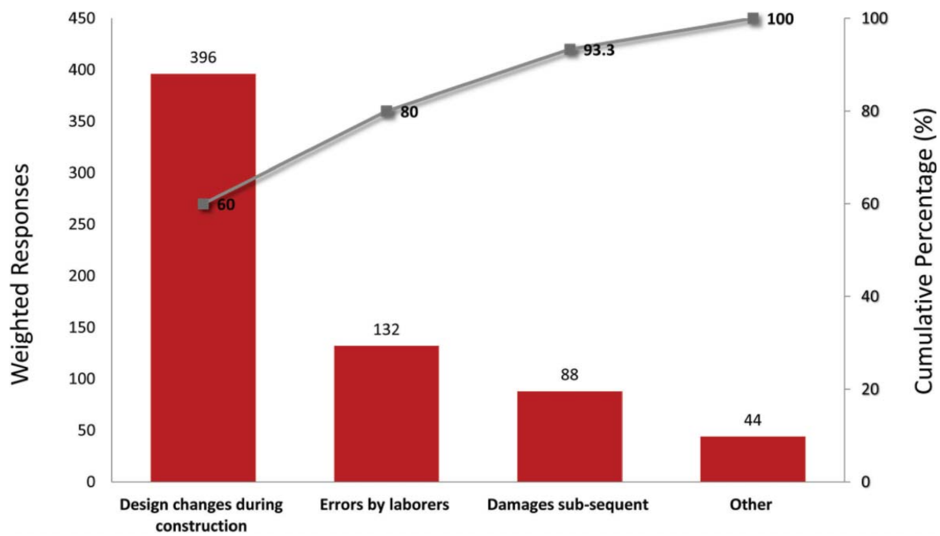

Figure 5. Pareto chart: Factors that generate most waste according to questionnaires for the pile cap process.

construction claims company. Respondents to the questionnaire had different backgrounds related to construction industry, including project managers, construction managers, site engineers, inspection engineers, quality engineers, planners and estimators. 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.

The Pareto Chart was then used to present the feedback revealed by the questionnaires. Each causal factor was given points based on how it was ranked in the employee questionnaire. The first place was assigned 4 points, 3 points for the second place, 2 points for the third place, and 1 point for any place after third. This scoring system was applied to each of the 30 responses. 'Design changes during construction' ranked first, representing 60% of the total points. 'Errors by labourers' ranked second, representing 20%. 'Damage to work done due to subsequent trades' ranked third, representing 13%. The remaining factors represented only 7% (see Figure 5).

The tabulated questionnaire results in similar rankings of causal factors as what is found in the literature (Bossink & Brouwers 1996; Formoso et al. 2002; Rojas & Aramvareekul 2003; Poon et al. 2004; Tam 2008). A majority of onsite workers concur that reducing or eliminating the likelihood of design changes during construction will help increase process performance by reducing waste. For example, establishing clear communications between involved parties, especially during the early phases of the project, will help reduce changes of design or procedure during the construction phase.

Finally, Step 3 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. This step is essential to framework as it is responsible for maintaining consistent successful performance and for continuous improvement.

To recap, this framework enabled us to apply the concept of DMAIC to the construction phase to improve the process. The sequence of steps starts with evaluating a chosen process, identifying the waste generated during the process and measuring its impact. Then, by using Six Sigma tools we were able to identify the possible reasons for the generation of the waste and could find suitable solutions to implement. Finally, the success of these solutions is monitored and revised business processes established to maintain improved performance.

Conclusion and future work

This paper explains 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. The two types of waste in the pile cap process studied were waste in materials and waste in time. The consumption of materials was the highest contributor in most environmental impact categories. Potential causes of waste were identified through a questionnaire and identified as design changes during construction.

The framework presented here has been designed to improve process performance during the construction phase of projects by reducing waste through a retrospective diagnosis. The developed framework is intended to evaluate environmental impacts of construction performance and to help contractors evaluate options to reduce the impacts of their traditional methods and improve the overall efficiency. Taking advantage of combining three important improvement methods Lean, Green, and Six Sigma is a major reason to differentiate the proposed framework. With this case study, we recognized two limitations: implementation time and the adequate experience to ensure reasonable and actionable results.

Errors and mistakes happen most of the time during construction due to the inherent complexity of the process. Typically, projects go through five phases during their life cycle, which include programming, design, construction, operation and demolition. For future work, we 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.

Supplemental data

Supplementary Data 1. A sample of the questionnaire sent to a construction consultant to be completed and an explanation for the rating system method used to calculate which factor causes construction waste most of the time.
Supplementary Data 2. Data input used for the pile cap process case study.

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