

MONITORING CARBON EMISSIONS IN PRECAST CONCRETE INSTALLATION THROUGH LEAN PRODUCTION – A CASE STUDY IN SINGAPORE

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ABSTRACT

The lean philosophy focuses on eliminating waste and maximizing productivity through the pull system, employee involvement, continuous improvement, etc. Much has been discussed about the waste elimination and productivity improvement that can be achieved by applying the lean concept. However, as the consideration of the environment is becoming an increasingly important part of the construction culture, there is a need to investigate the applicability of the lean concept to achieve environmental sustainability, which is often used interchangeably with the term “green”.

This research therefore aims to investigate the contribution of the lean concept to achieve low-carbon installation in precast concrete construction sites through a case study in Singapore. The life cycle assessment (LCA) results show that the lean concept can be adopted to reduce carbon emissions in terms of eliminating waste and inappropriate erection arrangements. In the installation cycle of a specific type of precast concrete column, an amount of 20.9kg carbon emissions (71.0%) is caused by wastes and inappropriate erection arrangements and can be reduced by applying lean principles through a detailed simulation. Many lean management practices in site layout, delivery, stock and erection management are identified in this paper. Based on the results, contractors can start to apply lean principles to improve the installation cycle and eventually achieve low-carbon installation.

KEYWORDS

lean production, prefabrication, sustainable development, carbon emissions, life cycle assessment

INTRODUCTION

Among all current environmental issues, climate change is the most significant one, by threatening human development (Tang and Yeoh, 2007). If actions are not taken to reduce greenhouse gas emissions, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP per year (Stern, 2007). The construction industry is constantly being challenged to reduce its large amount of energy consumption, raw material, and water usage (Low et al., 2009). According to Klotz et al., (2007), buildings consume 36 percent of the total energy used, 30 percent of the raw materials, and 12 percent of potable water consumed in the USA. AIA (2007) estimated that nearly 50% of all the GHG emissions are generated

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by buildings and their construction in terms of the energy used in the production of materials, transportation of materials from production factories to construction sites, as well as energy consumed in the operational stage. However, there is considerable potential to control and reduce carbon emissions in the construction industry with appropriate management. Various incentives have been established to promote low-carbon practices. For example, according to the Singapore Institute of Surveyors and Valuers (2008), the Clean Development Mechanism (CDM) Documentation Grant, where S\$100,000 worth of funding will be provided to encourage companies to develop CDM projects in Singapore. This fund has been launched by the National Environment Agency (NEA). In addition, carbon trading funds worth more than 250 million euros (S\$532.4 million) may be listed by the Singapore government for the building sector in the near future.

Many attempts have been made to reduce carbon emissions to achieve long-term sustainable development, including process and technology innovation (Spence and Muligan, 1995), adopting low-carbon fuels (Hendriks et al., 1999), identifying alternative low-carbon raw materials (Ellis, 2004), and CO₂ capture and sequestration (Herzog, 2001). However, it should be noted that nontechnical issues should not be overlooked when reducing carbon emissions, such as the improvement at the managerial level. Instead of relying solely on the carbon reducing technologies, project managers should be able to adapt to an open system where both the technical and nontechnical improvements are balanced. This research therefore aims to: a) highlight the relevance of the lean thinking in low-carbon erection at the construction sites using precast concrete products; and b) examine how lean thinking can be successfully applied at the construction sites using precast concrete products to achieve low-carbon erection. An in-depth case study of one construction project in Singapore will be examined for this purpose.

LEAN PRODUCTION PHILOSOPHY

Originated from the Toyota Production System (Ohno, 1988), the core of the lean production philosophy was the observation that there were two aspects in all production systems: conversions and flows (Koskela, 1992). Conversion activities referred to those which actually added value to the product/process. Flow activities referred to non-value adding activities that consumed time and resources but did not add value to the product/process. Traditional management improvement was not fully aware of the existence of these non-value adding activities, leading to efficiency being lost during production processes. The lean production philosophy aimed to create an environment where conversion and flow activities were treated separately. Conversion activities were improved while flow activities were eliminated.

The lean concept has proven to be effective in increasing environmental benefits by eliminating waste, preventing pollution, and maximizing value to owners (e.g. Huovila and Koskela, 1998; King and Lenox, 2001; Nahmens, 2009; Miller et al., 2010). Huovila and Koskela (1998) examined the contributions of lean construction principles to sustainable development and noted that such contributions included minimization of resource depletion, minimization of pollution, and matching business and environmental excellence. King and Lenox (2001) stated that lean production is complementary to environmental performance and is associated with lower emissions. Nahmens (2009) stated that it is a natural extension to apply the lean concept to achieve green production and construction. By applying the lean concept to a production line, 9 to 6.5 people (labor waste), 12% space (equipment waste),

and 10% wallboard (material waste) can be reduced (Nahmens, 2009). Miller et al. (2010) applied lean principles to a small furniture production company and found that lean principles can help the company meet every increasing customer demand while preserving valuable resources. The lean concept has also been proven to be effective in achieving environmental benefits in the manufacturing industry (Florida, 1996; Yang et al., 2011; Bergmiller, 2006; Wu and Low, 2012; Wu et al., 2013). In these studies, wastes, environmental burdens, and environmental deterioration were commonly used as the contributions that can be achieved by applying the lean concept. However, it appears that these contributions were too broadly described. It should be noted that the contribution of the lean concept to a certain application area can help to guide the preferred decisions and behaviours of the contractors. If the contribution is defined too broadly, the implications for the precasters will consequently be very minimal.

Unnecessary carbon dioxide in installation can be caused by:

- Waste of materials. The manufacture of cement and steel is highly energy intensive and can generate a significant amount of carbon emissions. For example, the manufacture of raw materials accounts for 76.1% of the total carbon emissions for a specific type of precast concrete column in Singapore (Wu and Low, 2011). If damaged, the precast concrete products need to be repaired.
- Fuel consumption. The use of installation and delivery vehicles, e.g. forklift trucks and delivery trucks, can generate carbon emissions in terms of fuel consumption.
- Electricity consumption. Similarly, the use of installation facility, e.g. tower cranes, can generate carbon emissions in terms of electricity consumption.

Based on the emission sources, many strategies can be taken to reduce carbon emissions by reducing the use of raw materials, eliminating waste, and improving energy efficiency. Some lean techniques that can be adopted to achieve the objective include:

- Grouping technology. Grouping technology is the method to organize the process/site layout in such a way that the work flow can be completed without unnecessary movements. For example, in precast concrete factories, cutting, bending and fixing operation sites should be located together to reduce the movements of fork-lifts, mobile cranes and lorries. Low and Chan (1996) found that the reinforcement steel bar bending yards and assembly yards were generally not located adjacent to the production beds. Transportation was to be arranged between the assembly yard and the production beds.
- Just-in-time (JIT). The term “JIT” means that the right parts needed are delivered to site at the time they are needed and only in the amount needed (Ohno, 1998). JIT can help to reduce energy consumption by eliminating transportation to and from the storage area because materials are used immediately when arrived.
- Uninterrupted workflow. The factory layout should be arranged in such a way that the process is not interrupted. This can be achieved through the implementation of product simplification by simplifying the work process. Preventive maintenance can also be used to achieve uninterrupted workflow.
- Total quality control (TQC). The term “total” refers to three extensions (Shingo, 1988): expanding quality control from production to all departments; expanding

- quality control from workers to management; and expanding the notion of quality to cover all operations in the company. By ensuring that every part of the production process is running at good quality, poor quality materials will not occur, thus eliminating materials and energy required to fix any problem.
- Employee involvement. The importance of employee involvement can be explained by the fact that organizational goals and personal goals can both be achieved if employees are treated with equity and respect in terms of being involved with decision making, being provided with meaningful jobs, and being given the opportunity to learn (Stendel and Desruelle, 1992).
- Continuous improvement. One of the most important instruments in the lean production philosophy is Kaizen or continuous improvement. Long-term commitment is necessary to build the lean platform to reduce carbon emissions.

A few studies have nevertheless suggested that lean implementation may yield a negative impact on environmental performance (Cusumano, 1994; Rothenberg et al., 2001; Bae and Kim, 2008). Rothenberg et al. (2001) found that there was a complex relationship between lean manufacturing and environmental performance that depended on the measure of environmental performance being examined. Bae and Kim (2008) stated that since the main purpose of lean is to provide excellent value for the customer rather than to reduce environmental impact, lean does not therefore always assure a positive environmental impact. According to Bae and Kim (2008), the difficulty in understanding and quantifying the impacts of the lean principles was perhaps one reason why stakeholders have hesitated to use lean principles to be green. It is therefore necessary to quantify the lean improvements before concluding that the lean concept can be applied in the precast concrete construction sites to achieve low-carbon installation.

METHODOLOGY

In accordance with the research aim of this study, which is to quantify how much carbon emissions can be reduced after lean implementations, the case study research method is appropriate (Yin, 1994). A high-rise condominium project in Singapore was chosen as the case study. The project was a typical case in Singapore using prefabrications in the construction project. The installation process of precast concrete columns was selected as the research target.

Data collection

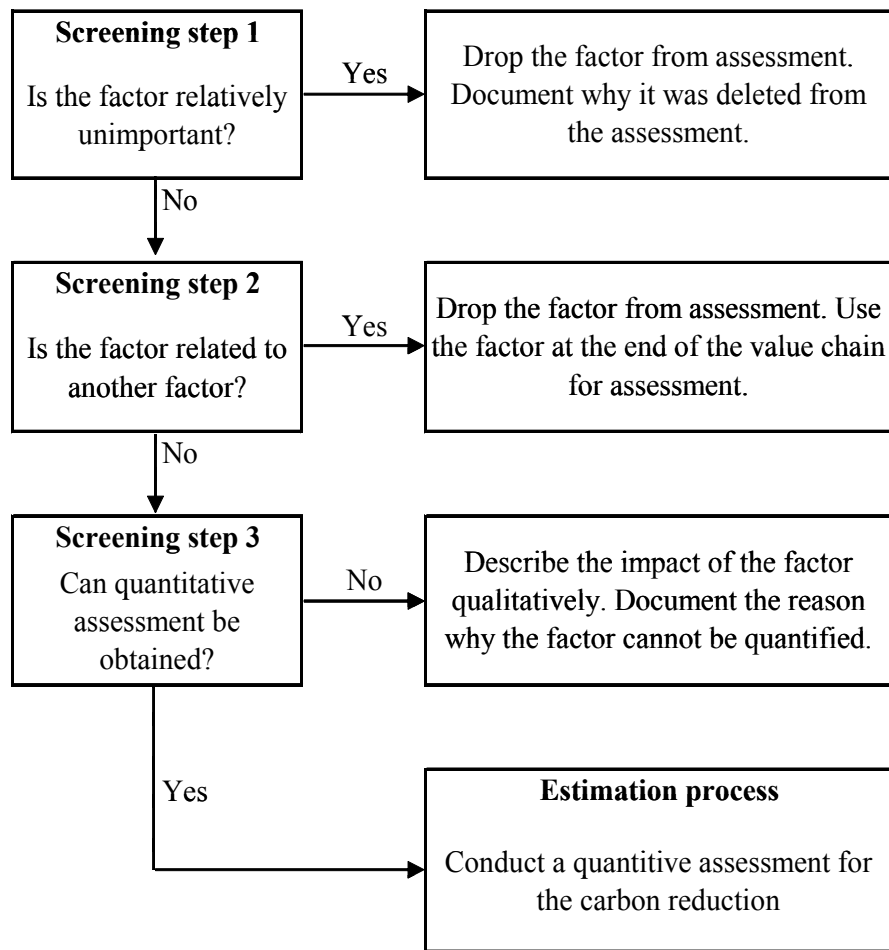
This study was part of a larger study that included, among other things, the production process of the precast concrete columns in precast concrete factories. The precast concrete column weighs 1.864 tons and the embodied carbon of the precast concrete column is estimated to be 609.59 kg (Wu and Low, 2011). To identify the non-value adding activities at the construction sites using precast concrete products, a catalogue was developed. The catalogue encompassed a comprehensive list of all the non-value adding activities that might occur in a typical construction site using precast concrete products from a lean perspective, such as the pull system, just-in-time, total quality control, employee involvement, etc. The list of non-value adding activities was obtained through literature review and surveys that were conducted with thirty contractors in Singapore.

The catalogue covered four sections: (1) site layout management; (2) delivery management; (3) stock management; and (4) erection management. A four-day site investigation was conducted at a condominium project of a contractor in Singapore. During the site investigation, direct observations were conducted to record the non-value adding activities on the construction site and semi-structured interviews were requested with the project manager to validate the non-value adding activities.

Data analysis

A general quantification procedure to quantify lean improvements was also developed for the contractor, as shown in Figure 1. The general procedure included two major subprocesses, which were the screening process and the estimation process.

FIGURE 1. A general procedure to quantify the lean improvements.



As can be seen in Figure 1, there were three subprocesses in the screening process, including:

1. Screening step 1: In this step, the relative importance of the non-value adding activity was rated by the probability of occurrence and the impact on carbon emission level. Non-value adding activities with no probability of occurrence or no impact on carbon emissions level were dropped from the assessment.

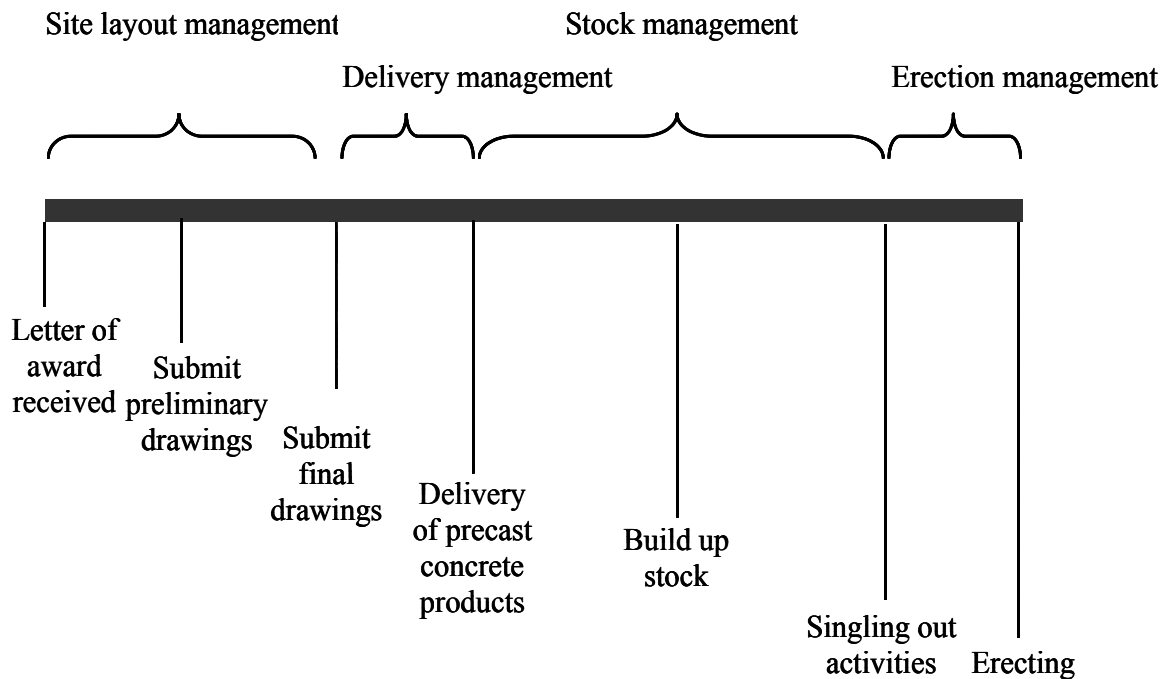
2. Screening step 2: Following step 1, non-value adding activities that required assessment were categorized into different groups, including equipment, electricity, waste of raw materials, waste of finished products, and capital facilities. Non-value adding activities under different groups were assessed by different equations (IPCC, 2008).
3. Screening step 3: Non-value adding activities that could not be categorized in any of the groups mentioned in step 2 might not be eligible for a quantitative assessment. Qualitative descriptions of the impact of such activities were needed and provided (Ross et al., 2002).

The estimation process followed the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC, 2008). World-wide average emission factors from the database were used where Singapore-specific emission factors were not available.

CASE STUDY

Life cycle assessment (LCA) has been widely adopted to evaluate the environmental impacts in both the manufacturing and construction sectors (Harris, 1999; Petersen and Solberg, 2002). Although an ideal LCA study should include all life cycle stages, restricted boundaries, such as cradle-to-gate and cradle-to-site, can also be used to estimate the environmental impacts through input-output analysis. A normal installation cycle of precast concrete products at the construction sites can be illustrated by Figure 2. The Life Cycle Inventory (LCI) data was investigated in each of the four value stages after production, which were site layout management, delivery management, stock management, and erection management.

FIGURE 2. The installation cycle of precast concrete products in the construction sites.



A few estimation criteria and assumption were made so that the calculation process could follow a standard procedure. The estimation criteria included:

1. System boundaries. As can be seen from Figure 2, major processes that should be calculated in this study included (1) delivery of precast concrete products; (2) building up stock; (3) singling out activities; and (4) installation.
2. Data selection. Singapore-specific emission factors were preferred, such as the emissions factors for electricity generation. These emissions factors are shown in Table 1.

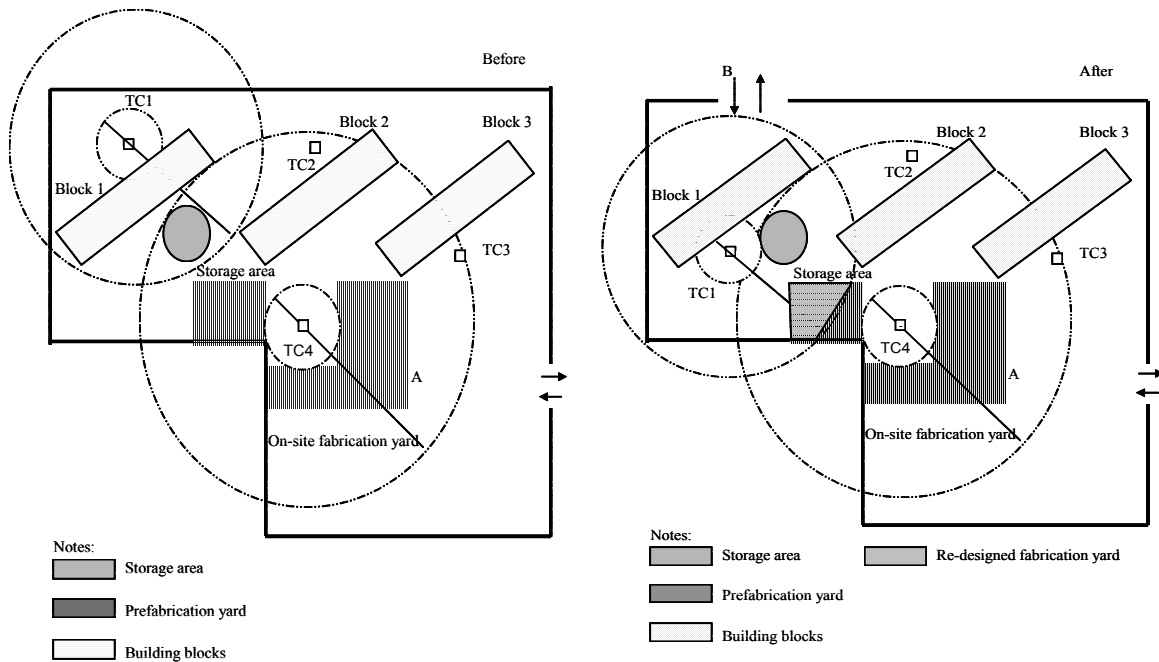
TABLE 1. Energy consumption and emissions factors used in this case study.

Energy consumption and emissions factors	Sources
Carbon emissions from road transportation (120g/ton.km)	Peyroteo et al. (2007)
Carbon emissions from the idling of delivery vehicles (10,397 g/hour)	U.S. DOE (2000)
Energy consumption of tower crane (Table 2)	Provided by contractors
Carbon emissions of tower crane (Table 2)	Derived from energy consumption of tower crane

In accordance with the estimation criteria, a few estimation assumptions were made to calculate the carbon emissions generated in a complete erection cycle. These estimation assumptions included:

1. Round trip local road transportation distances were estimated to be 15 miles (24.15km) based on the geographical location of the precast concrete factories.
2. Energy consumption per erection cycle was calculated by the following procedure:
 - Six precast concrete columns were transported from the precast concrete factory to the construction site.
 - Tower crane was used to erect the precast concrete columns. Six precast concrete columns were installed in one hour on the floor level with a height of 103.6m.
3. The site layout of the project is shown in Figure 3 (before). As shown in Figure 3, four tower cranes were used to build three building blocks. A combination of both on-site fabrication and off-site fabrication was adopted in this project. The precast concrete columns as well as some other precast concrete products such as window frames and staircases were ordered from the precast concrete factories. A few types of precast concrete products such as planks and beams were fabricated in the prefabrication yard. Tower crane (TC) 1, 2, and 3 were used to conduct erection activities for the respective building block, while TC 4 was used to conduct transferring activities for the precast concrete columns from point A to the storage area and on-site production activities. In this study, only TC1 and TC4 were considered and only the storage area for Block 1 was shown in the site layout plan.

FIGURE 3. Site layout of the project (before and after implementing the lean concept).



- The details of the cranes used in the erection processes are shown in Table 2. This study chose Building Block 1 as the research objective. Only TC1 and TC4 were used in the erection processes of Building Block 1. TC1 was used to conduct erection activities for block 1 while TC 4 was used to conduct transferring activities for the precast concrete columns from point A to the storage area and on-site production activities.

TABLE 2. Fuel consumption and emissions factors of the tower crane.

Tower crane number	TC1	TC4
Fuel consumption (normal operations) Litre gasoline per hour	7	6
Fuel consumption (full operations) Litre gasoline per hour	14	12.5
Emission factor (normal operations) Kg CO ₂ per hour	18.76	16.08
Emission factor (full operations) Kg CO ₂ per hour	37.52	33.5
Emission factor used in this study Kg CO ₂ per hour	18.76	16.08
Emission factor source: U.S. Energy Information Administration (2010)		

Site layout management

The site layout of the construction project was carefully planned. According to the project manager, this site layout was sent to the consultants for approval. The siting of the tower crane and parking of the mobile plants were also carefully planned to achieve economic and efficient erection. The contractor did not over provide for material storage area in terms of secured store, weatherproof store and open store. The storage area was designed to store the precast concrete products that would be used in the following one or two days. However, several non-value adding activities should be highlighted from a lean perspective. These non-value adding activities included:

Green building materials. In this project, normal concrete was adopted from the 1st to 20th storey. Green concrete was used from 20th storey to the roof. This decision was made based on two reasons:

- Columns from the 1st to 20th storey required a high strength concrete of Grade 50 (G50) and above, while columns from the 20th storey to the roof required a concrete strength of G35. Current green concrete design might not be very stable under high strength--a concern expressed by the project manager. More tests should be conducted when using high grade green concrete.
- Using the green concrete from the 20th storey to the roof would achieve the objective that 60% of the total volume of concrete was the green concrete. This could enable the project to obtain the Green Mark (BCA, 2008) point which required that 50% of the total concrete volume was green concrete.

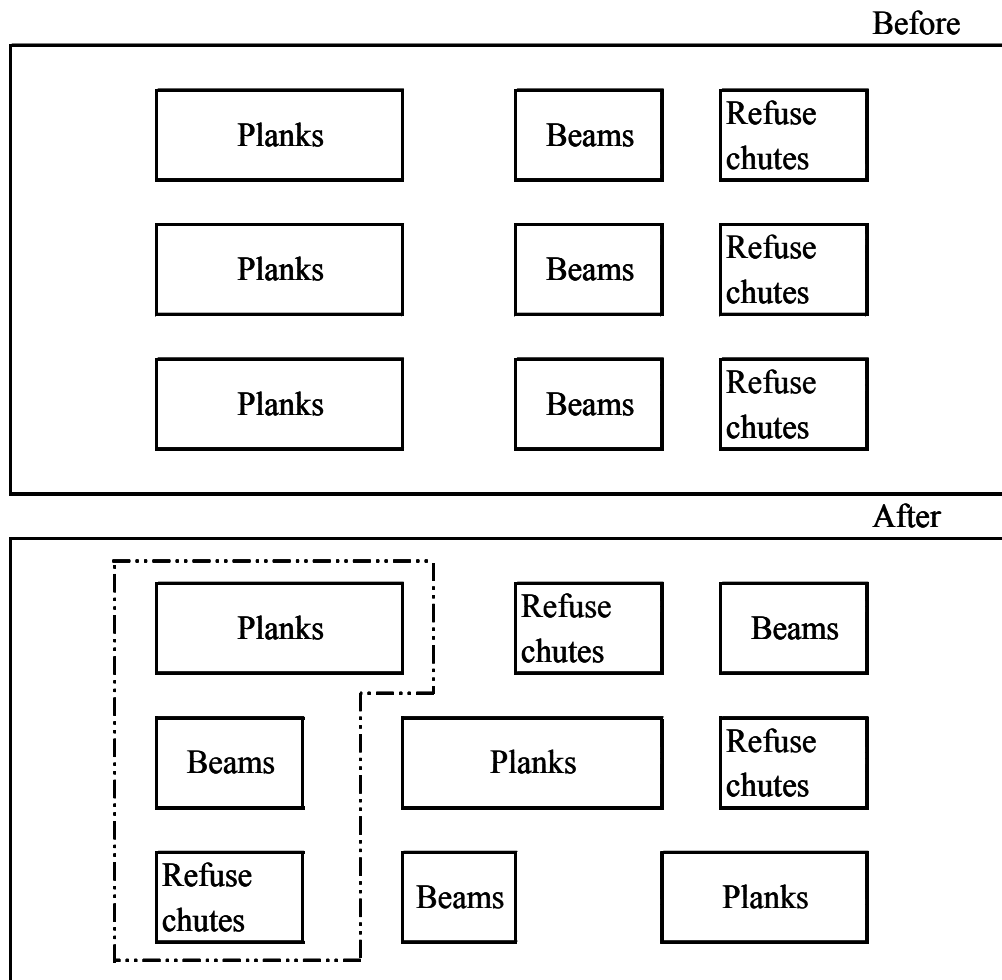
A detailed discussion with the green concrete supplier was conducted to validate the above two points. As for the first point, G50 green concrete was not widely used at the time of this study. The G50 green concrete was only used in a few projects. The performance of the green concrete was not a problem as stated by the supplier. It was the price of the green concrete that might impede its full use throughout the project. It should be noted that the G35 green concrete per cubic metre was more expensive than the G35 normal concrete by almost S\$5, which would cause the revenue of the project to decrease by about S\$170,000. If green concrete of a higher grade was used in this project (e.g. the G50 green concrete), the profitability of the project could be reduced sharply.

The lean thinking proposed that the fundamental problems were to be identified and resolved. However, it seems that there was a problem of point chasing in this project for green certifications. The contractor was merely fulfilling the minimum requirements of the green rating system rather than developing a genuinely green project. However, this is not to suggest that the contractor was wrong in doing so by fulfilling the minimum requirements based on economic considerations. Promoting green building materials through the whole project could be supported and subsidized by the government (e.g. the CDM Documentation Grant and carbon trading funds in Singapore as mentioned earlier) so that fundamental problems leading to high carbon emissions could be solved without the influence of economic considerations.

Site layout design. By using both on-site fabrication with off-site fabrication, economic savings could be achieved for the contractor. However, the design of the area for on-site fabrication should be conducted carefully. At the construction site, the following procedure could be taken to improve the workflow from a lean perspective (e.g. grouping technology):

- Step 1 – Re-allocate TC1 to achieve immediate usage of the precast concrete products produced in the on-site fabrication yard. As can be seen in Figure 3 (before), the overlapping area of TC1 and TC4 was the storage area for the precast concrete products that would be used for Block 1. The precast concrete products produced at the on-site fabrication yard were transferred to the storage area for installation. Such transferring activities were not adding value to the erection process when examined by lean thinking. It is proposed that TC1 be re-allocated so that direct usage of the precast concrete products could be achieved. This re-allocation process can be seen in Figure 3 (after).
- Step 2 – Re-design the on-site fabrication yard. Following the re-allocation of TC1, the on-site fabrication yard should be re-designed to facilitate immediate usage, which is referred in lean terminology as the pull system. As illustrated in Figure 4 (before), under normal circumstances, the production of the precast concrete products was organized in such a way that each type of product was produced in a separate section of the site layout. This was the strategy that the contractor adopted for on-site. However, it is proposed that another grouping strategy should be adopted to achieve low inventory and smooth work flow, as shown in Figure 4 (after).

FIGURE 4. On-site fabrication yard (before and after implementing the lean concept).



The strategy adopted was to group the precast concrete products that were used in Building Block 1 into an area so that TC1 could conduct the installation activities once the precast concrete products were produced. Unlike the traditional production arrangement, this strategy would enable the contractor to conduct immediate installation without transferring activities and inventory to make the construction activities flow without interruptions.

- Step 3 – Create another entrance at location B, as shown in Figure 3 (after). Another entrance should be opened at location B to facilitate the delivery of other precast concrete products (columns, window frames, and staircases) to Building Block 1. These precast concrete products would therefore not be transferred by TC4 to the storage area for installation. Immediate installation could be arranged for Building Block 1 if an entrance B was created.

An amount of 2.0kg carbon emissions was recorded by transferring the precast concrete column from location A to the storage area. This amount of carbon emissions could be reduced if the above lean site management practices were applied.

Delivery management

The delivery of the precast concrete columns from the precast concrete factories to the construction site was operated by a subcontractor. An “all-in-one” price was adopted so that the contractor could focus on erection and other construction activities. The quantities required in the following one or two days were carefully estimated. Based on the estimated quantities, the precast concrete columns were delivered to the construction site, unloaded at the storage area, and installed when needed. The contractor was not facing demand fluctuations. According to the project manager interviewed, although there would be small changes in the quantities of the precast concrete columns from day to day, such changes were very small and a stable erection schedule could be anticipated. It seems that the just-in-time (JIT) delivery system (Tommelein and Li, 1999) can be applied in this project because of the stable erection schedule and the satisfactory performance of subcontractors. However, following the screening procedure, the contractor appeared to face several problems in delivery management from a lean perspective, which included:

Transportation. As observed at the construction site, the delivery time caused many interruptions to the erection process. The delivery time of ready mix concrete (for on-site fabrication) and the delivery time of the precast concrete columns overlapped, causing the delivery vehicles to idle on the road for 5 minutes to 30 minutes. During the site investigation, these idling vehicles often happened and generated a significant amount of carbon emissions. An average idling time of 15 minutes was assumed for each delivery of precast concrete columns, which equals to an amount of 2.6kg CO₂ emissions per delivery or 0.4kg CO₂ emissions per column per delivery.

Tommelein and Li (1999) proposed that a two-order system, which was also referred to as the JIT delivery, should be adopted to manage the delivery. In the advance order, approximate quantities and the delivery time were defined to reserve site capacities on the delivery day. A few days prior to the actual delivery date, confirmation order (or release order) must be sent to the contractor to confirm the previously agreed delivery, including quantity, delivery date and time. Modifications could therefore be made to previous advance orders. However, it

should be noted that such modifications should be kept to a minimum as deviation from the planned schedule would increase cycle time and might interrupt the delivery process. If the above lean delivery management practices are applied, 0.4kg carbon emissions can be reduced.

The arrival of finished products. The contractor was not fully prepared for the arrival of the precast concrete columns. The human resources allocated to facilitate the delivery, loading and unloading activities, were not enough. No traffic controllers were even provided at the main gate to facilitate the movement of the delivery vehicles. According to Richardson (1973), it is advisable that one person, or in the case of large contracts, one group of people, at the precast works be made responsible for the arrangements for delivery of elements and equipment so that errors caused by wrongly passed messages can be avoided. In addition, the site layout was not designed with lean thinking, which leads to traffic congestion at the main gate. The drawbacks of the site layout design have been explained earlier.

Typical damages during transportation. Damage to the precast concrete columns were common during transportation. However, such damage was very small and can be rectified by repairs. Typical damages included: 1) broken nibs and corners; 2) damage due to the wrong placement of battens 3) damages to slender sections; and 4) damage caused by the use of slings and chains. According to the project manager interviewed, a 2% waste of finished products could be anticipated. An amount of 12.2kg CO₂ would be emitted by replacements or repairing activities. Sufficient care should be provided in the delivery process by the vehicle drivers. According to the project manager interviewed, such damage could be reduced if sufficient care was provided when conducting loading and unloading activities, as well as during transportation. It is recommended that a certification programme be designed to examine whether or not the employees are able to handle the precast concrete columns without damage during transportation, which may be similar to the Freight Operator Recognition Scheme in the UK. If the above lean delivery management practices were applied, 12.2kg CO₂ emissions can be reduced.

Stock management

According to the contractor, appropriate equipment (which is the tower crane in this case) was selected to manage the storage, which was maintained by a well-trained staff. There was no wrong use of the precast concrete columns due to unclear identification marks. The main non-value adding activities from a lean perspective included:

Lack of well-ordered stockyard. The stockyard was not well maintained, especially the on-site fabrication yard. During heavy rain, the stockyard was water-logged. Pumping activities were non-value adding activities that caused an increase in the carbon emissions level. The drainage of the site could be improved to avoid potential damages to the precast concrete products. The lean concept advocated that non-value adding activities be identified at the very start to avoid interruptions to production activities, which included a well-maintained stockyard.

Inappropriate battens. Some precast concrete products were stacked without using the appropriate battens. This omission would cause damage to the precast concrete products. The working instructions provided to the employees who were in charge of stock management were made in terms of on-the-job training. A detailed programme including the stacking requirements was not provided by the contractor. While it is proposed that the use of more than two battens along the length should be avoided except for extremely flexible prestressed planks (Richardson, 1973), this procedure was not always followed by the contractor. Lean thinking

encourages the idea of employee involvement, the importance of which could be explained by the fact that organizational goals and personal goals could both be achieved if employees were treated with equity and respect in terms of being involved with decision making, being provided with meaningful jobs, and being given the opportunity to learn (Stendel and Desruelle, 1992). The contractor needed to involve employees in training programmes to avoid such damages. Appropriate trainings on carbon management should be provided. Written directions including the stack requirements should also be provided. If appropriate stacking requirements were provided, damages during inventory could be reduced, which could bring down the carbon emissions level by 6.1kg.

Lack of periodic stock checks. According to the contractor, the quantity of the precast concrete columns used in this project was carefully estimated. The quality of the precast concrete columns was checked in the precast concrete factories before these products were arranged for delivery. Periodic stock checks were therefore unnecessary at the construction site because the precast concrete products would be used in the following one or two days. However, it should be noted that one important aspect in the lean concept was to make production flow without interruption. Periodic stock checks would be useful to identify and avoid the following interruptions:

- Potential damages due to inappropriate stacking;
- Unanticipated rejection of the precast concrete columns due to unsatisfied quality; and
- Installation delays caused by adverse weather conditions.
- According to the contractor, the damages to the finished products in the storage area were very minimal (normally in an amount of 1%). Small repairs would be conducted if such damages were found.

Erection management

The contractor provided a written erection method statement and a video tape to guide the erection activities. According to the project manager, such a statement was prepared so that issues relating to health and safety could be properly addressed. By following the procedures listed in the erection method statement strictly, deviations from the planned procedure could be eliminated. Erection activities were carried out with appropriate staff arrangements at the construction site. Four persons were allocated to conduct the erection activities, including two charge-hands, a banksman, and a crane driver. According to the project manager, erection accuracy was satisfactory. Once the precast concrete column was placed at the right position, there would be no further movement of the column.

The continuous improvement plan of the contractor was good enough to support further improvements. Internal periodic meetings were organized every week to discuss further improvements. Consultants were involved in the periodic meetings every two weeks. However, it should be noted that lean experts should also be involved in such periodic meetings. There were many activities that were considered as value adding activities, but should be categorized as non-value adding activities examined by the lean production philosophy, such as storage, bufferstock, and transferring activities. The non-value adding activities relating to erection management included:

Inappropriate crane operations. The precast concrete columns were used based on a “deliver-store-use” method. The precast concrete columns were stored in the storage area

located at the side of the building block before these were arranged for erection in the following one or two days. Loading and unloading activities at the storage area would cause double handling and possibly damage the products. According to the project manager, 1% damage to the precast concrete columns could be anticipated during the storage.

The other source of carbon emissions caused by using the “deliver-store-use” method was the slinging out and transferring activities. As observed in the construction site, TC4 was used to conduct the singling out and transferring activities, as well as the casting activities for some on-site prefabricated products, such as window frames, staircases, etc. However, other than the production arrangements, all other activities were identified as non-value adding to the erection process from a lean perspective. A total of eight precast concrete products were transferred in one hour and an amount of 16.1kg of CO₂ was emitted as unnecessary emissions. When such inappropriate crane operations were eliminated, an amount of 2.0kg carbon emissions could be reduced.

Inexperienced employees at the construction site. As observed at the construction site, a smooth work flow was not always followed. There were a few interruptions to the work flow which were caused by inexperienced employees. These interruptions included:

- When transferring the precast concrete column from the pick-up point (location A as shown in Figure 3) to the storage area, the precast concrete column is suspended for almost 5 minutes when the employees attempted to make a place for the column in the storage area. This non-value adding activity happened every day in the four consecutive days of observations.
- Due to the on-site fabrication of other precast concrete products, TC4 was heavily used. The use of TC4 did not follow a smooth work flow. When TC4 was arranged to pick up the precast concrete column at the pick-up point (location A), the crane operator was told to conduct the demoulding work instead. Such unnecessary swings of the jib would cause an increase in the level of carbon emissions.
- The position where the precast concrete column should be installed was marked with a clear line in the construction site. Erection accuracy should be checked before releasing the precast concrete column. However, some steps of the erection accuracy checks were conducted after the release of the precast concrete column. For example, a ruler was used to check whether the alignment of the precast concrete column relative to the marked point was straight. This accuracy check was conducted after the precast concrete column was released from the tower crane, which might cause double-handling when the accuracy check was not satisfactory.
- A lean benchmarking process to learn from the best employees was not created on site. According to Knuf (2000), a lean benchmarking process is of vital importance to the management of knowledge and practice of continuous learning and improvement.

After the lean implementations, the unnecessary swing of jibs, suspension of precast concrete columns, and double handling can be eliminated, thus reducing carbon emissions.

Inadequate supervision during erection processes. The supervision at the construction site was not enough to support a smooth work flow. Some activities caused interruptions to the work flow. These non-value adding activities included:

- The erection activities at the construction site were not always conducted by the integrated site team, which should usually include one banksman, one crane operator, and two charge-hands. As observed at the construction site, the banksman who should direct the operations of a crane was also conducting the work that should be handled by the charge-hands—all of which led to the sudden accelerating and braking of equipment.
- The precast concrete column was usually suspended for 1-3 minutes before erection activities were conducted. The banksman and charge-hands were asked to conduct some other works at the construction site, while the precast concrete column was suspended. This interrupted the work flow and caused an increase in the level of carbon emissions. During the two-hour site visit for four consecutive days, this happened every day.

With lean principles senior level management can remedy the inadequate supervision during the installation process and improve it. Carbon emissions (0.1kg) caused by unnecessary suspension of precast concrete columns can be eliminated.

RESULT AND DISCUSSIONS

As explained earlier in Table 1, an emissions factor of 0.12kg CO₂ /km/ton is adopted to calculate the carbon emissions during transportation. A total of 5.4kg (0.12 x 24.15 x 1.864) CO₂ was emitted during transportation. In addition, a total of 3.1kg CO₂ was recorded when installing one precast concrete column to a height of 103.6m. The breakdown of the carbon emissions in one complete erection cycle is shown in Table 3. This amount of carbon emissions (8.5 kg CO₂/column) is referred to as effective carbon in the following context because it is caused by value adding activities. Effective carbon is calculated in an installation cycle where there are no non-value adding activities or wastes. The installation work of the precast concrete columns could not be completed without generating this amount of carbon emissions.

TABLE 3. Carbon emissions in one complete erection cycle without non-value adding activities.

Category	Carbon emissions Kg CO ₂ /column
Transportation of the precast concrete columns from the precast concrete factories to the construction site	5.4
Erection of the precast concrete columns from the delivery vehicle to the building block	3.1
Total	8.5

The amount of carbon emissions that could be reduced by implementing appropriate lean technologies is shown in Table 4.

TABLE 4. Carbon reduction achieved by applying the lean production philosophy.

Category	The amount of carbon emissions (Kg CO ₂ /column)	Lean technology
Waste of finished products	18.3	
Typical damage during transportation	12.2	TQC
Lack of well-ordered stockyard	6.1	Employee involvement/ Uninterrupted workflow
Inappropriate battens		
Lack of periodic stock checks		
Inappropriate crane operations		
Inappropriate installation arrangement	2.5	
The site layout is not carefully planned to achieve economic and efficient productions	2.0	Grouping technology/ Uninterrupted workflow
Inappropriate crane operations		
Transportation is not taken into consideration	0.4	JIT
Not fully prepared for the arrival of the finished products		
Inexperienced employees at the construction site	0.1	Employee involvement
Inadequate supervision during erection processes	0.05	Employee involvement
Other qualitatively described lean improvements	Please refer to the qualitative assessment for each factor	
Does not think of green building materials		
The site layout is not carefully planned to achieve economic and efficient production		
Inexperienced employees at the construction site		
Inadequate supervision during erection processes		

As can be seen from Table 3 and Table 4, the carbon emissions during the erection processes could be represented by the following formula:

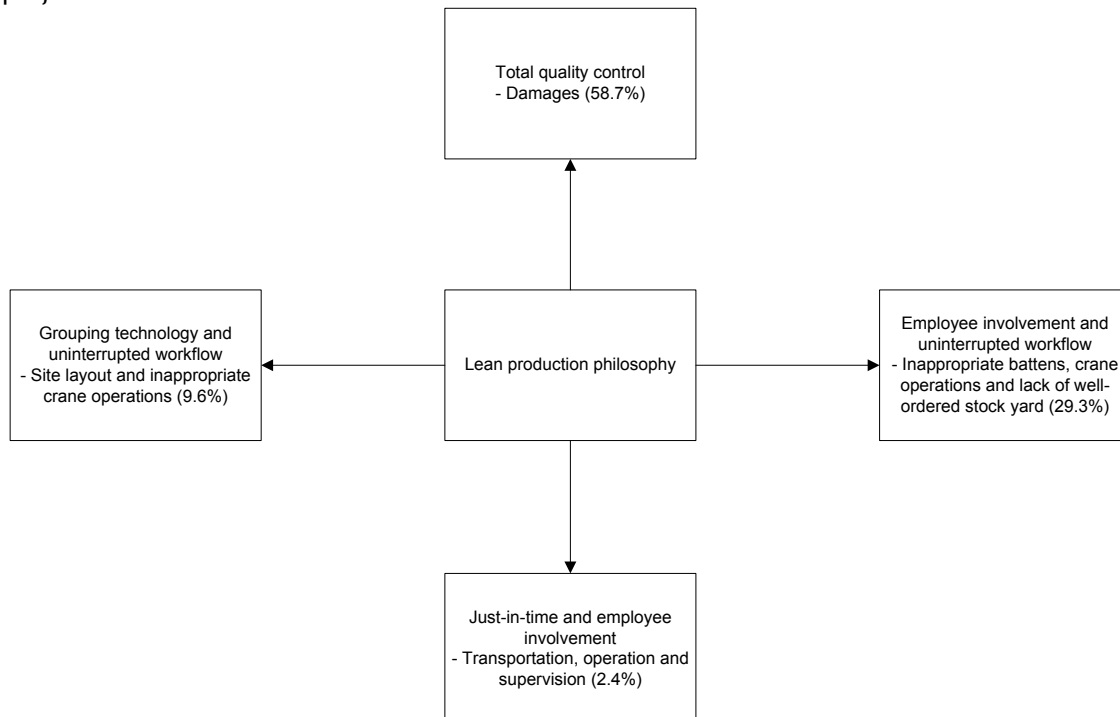
$$\text{The amount of CO}_2 = \frac{8.5}{\text{Effective carbon}} + \frac{18.3}{\text{Wastes}} + 2.5 \text{ (kg)}$$

A total amount of 20.8 kg of CO₂ (80.0%) was emitted in terms of waste of finished products and inappropriate installation arrangements. This amount of carbon emissions was 2.45 times greater than the effective carbon. 18.3 kg of CO₂ (62.5%) was emitted in terms of wastes of finished products, either during transportation or during storage. Another amount of 2.5 kg of CO₂ (8.5%) was emitted in terms of inappropriate installation arrangements, such as inefficient site layout, inappropriate crane operations, inexperienced employees and inadequate supervision. The details of the breakdown are shown in Table 5 and Figure 5.

TABLE 5. The breakdown of carbon emissions.

Category	The amount of carbon emissions (Kg CO ₂ /column)	Percentage (%)
Effective carbon	8.5	29.0%
Wastes of finished products	18.3	62.5%
Inappropriate installation arrangements	2.5	8.5%
Total	293	100%

FIGURE 5. The contribution of lean technologies to the reduction of carbon emissions in this project.



The decision to use green building materials to reduce carbon emissions in construction projects was highly dependent on the green building certification programmes. It appears that such decisions were not made based on the intention to reduce carbon emissions but on the intention to obtain scores in green building certification programmes. As stated previously,

facilities managers and employees who are working closely with equipment should have the greatest potential to reduce carbon emissions at construction sites. However, the competence of the facilities managers and employees could be improved. Many non-value adding activities happened at the construction sites because the employees lacked a vision of smooth work flow. All preparatory work should be completed before the installation work can start. For example, when observing the delivery of finishing sands (which are contained in fabric bags) to the construction site, it is found that the wooden supports for such bags (so that these bags of sands can be transferred using forklifts) were provided while the delivery vehicle was kept idling. In addition, during one day of the site observation when there was a heavy rain, the air compressor was left running for almost one hour until the rain stopped. Although these non-value adding activities were not within the scope of this study, this does not mean that these activities were not important. When a typical 2HP air compressor was left idling for one hour, almost 0.8kg of CO₂ will be emitted (based on the emission factor for electricity generation of Singapore). This amount of carbon emissions is 30.0% of the effective carbon when installing the precast concrete columns to the 31st storey in this study. As more project management and environmental management practices and processes will be considered in green building rating systems (Wu and Low, 2010), such non-value adding activities may affect the certification of the construction project.

In this study, equipment idling was a serious problem. This might be caused by using on-site fabrication with off-site fabrication. While on-site fabrication could usually bring economic savings, the site arrangements and transportation arrangements should be more carefully prepared than using off-site fabrication alone. In this case, both site arrangements and transportation arrangements could be improved to prevent equipment idling to reduce carbon emissions. In fact, if equipment idling was listed as one of the consideration in BCA Green Mark certification, this project might fail for this criterion.

The results derived from this case study were obtained from a detailed simulation. It may be difficult for contractors to reduce all non-value adding activities at the very start. However, it is good practice to start applying some lean principles, e.g. the grouping technology, smooth work flow, which will help reduce carbon emissions. In addition, different contractors may face different non-value adding activities. The non-value adding activities at each construction site should be identified case-by-case. The amount of carbon emissions that can be reduced by applying the lean philosophy may vary significantly depending on the frequency of the on-site non-value adding activities. However, as stated previously, this case is a typical case in the Singapore construction industry. The results can be used for “analytic generalization” purposes (Yin, 1994). Contractors can use the same procedures presented in this case study to identify their own on-site non-value adding activities and quantify the carbon reduction.

The results of this study also have an implication on current carbon labelling practices (Wu et al., 2014). Carbon labels for concrete are established in many countries, such as the Singapore Green Labelling Scheme (Singapore), the Hong Kong Carbon Labelling Scheme (Hong Kong), CarbonCounted (Canada), and CarbonFree (US). The majority of these carbon labels use cradle-to-gate as the system boundary, claiming that installation activities and the following use and end-of-life phases have minimal impact on the life cycle GHG emissions of concrete. However, none of these studies use sensitivity analysis to justify the decisions to exclude these life cycle stages. In this case, installation activities account for 4.5% of the GHG emissions in pre-use stages. The 4.5% far exceeds the 1% threshold proposed to exclude

an emission source in international GHG standards, e.g. in Publicly Available Specification (PAS) 2050.

The use of cradle-to-gate is also restricted in the recently published ISO 14067, which clearly states that cradle-to-gate can be used as the system boundary in carbon labelling schemes only if (ISO 14067, 2013):

- information on specific stages (e.g. the use and end-of-life stages of the product) is not available and reasonable scenarios cannot be modelled; or
- there are stages that are insignificant for the GHG emissions and removals of the product.

For example, the Hong Kong Carbon Labelling Scheme uses cradle-to-site (i.e. from extraction of raw materials to the border of Hong Kong) as the system boundary to assess the carbon emissions of cementitious materials (e.g. precast concrete). If the Construction Industry Council, which is the founder of the scheme, wishes to continue the program using cradle-to-site as a system boundary, the council should prove that the installation, operational and demolition stages of precast concrete have minimal impact on its life cycle GHG emissions. This cannot be achieved because according to the results of this study, installation cycles account for 4.5% of the carbon emissions in the pre-use phase. Many other studies have found that the use and end-of-life phases of concrete can also have a significant impact on its life cycle GHG emissions, which is highly influenced by the way concrete is handled after demolition (e.g. Pade and Guimaraes, 2007; Collins, 2010). These life stages can also be appropriately modelled through many well established modeling techniques, such as Building Information Modelling (see Stadel et al., 2011), GaBi (see Loijos, 2011) and SimaPro 7 (see Cass and Mukherjee, 2011). Therefore, under the regulations for carbon labelling schemes proposed by ISO 14067, the Construction Industry Council will have to change the system boundary to cradle-to-grave because neither of the two exclusions can be met.

CONCLUSIONS

This research validates that the lean production philosophy can be applied at construction sites using precast concrete products to achieve low-carbon production. A total amount of 29.4kg carbon emissions is generated in the installation cycle of one precast concrete column. Two major categories that may cause an increase in the level of carbon emissions are waste of the finished products (18.3kg) and inappropriate installation arrangements (2.5kg). Only 29.0% of the carbon emissions generated is value adding to the installation cycle. On the other hand, nearly 71.0% of the carbon emissions is emitted by non-value adding activities and can be reduced in the installation cycle if appropriate lean management practices are applied. There seems to be a great efficiency loss in the installation cycle.

It is therefore proposed for contractors that a few lean issues should be focused upon to achieve low-carbon erection at construction sites. A value stream mapping (VSM) process should be conducted at the construction sites to fully identify the non-value adding activities. Facilities managers and employees who are working closely with equipment have the greatest potential to reduce carbon emissions at construction sites and should be appropriately trained to conduct a smooth work flow. Equipment idling is a serious problem in this case study. It

appears timely for Singapore to take steps to develop laws and regulations to raise the operators' awareness to restrict vehicles from idling.

The lean production philosophy can also help the contractors improve their project management and environmental management practices. Upon the achievement of such improvement, contractors may obtain better scores in the green building certification programmes, such as the BCA Green Mark Scheme. It should be noted that other benefits associated with low-carbon erection can also be achieved by applying the lean concept, which may include: reduced inventory, reduced floor area, short installation time, decreased probability of defects and re-work, and increased efficiency.

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