

# DEVELOPING A LEAN BENCHMARKING PROCESS TO MONITOR THE CARBON EFFICIENCY IN PRECAST CONCRETE FACTORIES—A CASE STUDY IN SINGAPORE

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## ABSTRACT

*The lean production philosophy was developed in the automobile industry and put into practice in the manufacturing industry to reduce waste, inventory and improve productivity. The lean concept has recently been introduced to the manufacturing industry to meet the challenge of sustainable development. However, it seems that the concept of sustainable development was defined too broadly for the manufacturers to guide their preferred decisions and behaviours. This research aims to narrow down the concept of sustainable development and focus on the carbon emissions that can be reduced by applying the lean concept in the precast concrete factories. The results demonstrate that the lean production philosophy can help precasters to reduce the level of carbon emissions, in terms of reducing waste and eliminating unnecessary energy consumption in multi-handling, multi-delivery, maintaining inventory and other non-value adding activities, in line with its concentration on eliminating non-value adding processes. An amount of 5.80% carbon emissions can be reduced in the production process for a specific type of precast concrete column. The lean benchmarking process provided in this study is helpful for the precasters to monitor the carbon efficiency in the precast concrete factories. In addition, the analysis provides good practice guidance when precasters are trying to reduce carbon emissions to meet guidelines from regulatory authorities.*

## KEYWORDS

sustainability, concrete fabrication, prefabrication, environmental impact, lean

## INTRODUCTION

Among all current environmental issues, climate change seems to be the most significant one, which causes the most considerable threat to human development (Tang and Yeoh 2007). The potential impact of climate change on the global economy could be enormous: re-insurance companies estimate that it could be of the order of hundreds of billions of dollars per year in the form of natural disasters and disruptions to agricultural cycles (Brown 2005). If actions

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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, now and forever (Stern 2007). Climate change is mainly caused by increase in greenhouse gas (GHG) emissions from both natural and man-made sources. However, it is widely believed that man-made sources, such as human activities, are the most significant factors.

The construction industry plays a significant role in the economic growth around the world. In the UK economy, the construction industry accounts for 8 percent of GDP and employs 1.5 million people (1 in 14 of the total working population) directly (Brown 2005). However, this industry is now highly challenged as the largest source of GHGs. According to the American Institute of Architects (2007), it is estimated that nearly 50% of all the GHG emissions are generated by buildings and their construction in terms of energy used throughout the life cycle.

The Singapore Construction 21 Committee (1999) encouraged contractors to use precast concrete products because of their benefits towards faster construction, fire protection, productivity improvement, etc. Glass (2000) observed that the market for precast concrete was rising due to the large demand for prefabricated housing in the UK, Germany, the Netherlands and other developed countries. Precast concrete products were believed to have some “green” benefits, such as reducing waste, improving total quality, reducing energy consumption and carbon emissions (e.g. Elhag et al. 2008; López-Mesa et al. 2009; Chen et al. 2010). However, it is found that the precast concrete industry can be improved towards environmental sustainability before it can support the construction industry to meet the challenge of sustainable development. Low and Mok (1999) found that the prefabrication yard can be improved by lean principles to improve productivity. Ballard et al. (2003) applied lean principles to a work flow and found that substantial improvements in performance can be achieved with little capital investment and without changing technology or how specific operations were performed. Ko (2010) found that the pull-based production method can effectively lower the inventory level in precast plants. It seems that the precast concrete production has the potential to be improved to achieve low-carbon production.

This research therefore aims to: (a) highlight the relevance of the lean concept in achieving low-carbon production; (b) identify the non-value adding activities in precast concrete production from a lean perspective; and (c) quantify the carbon emissions that can be reduced by applying the lean concept. The amount of carbon emissions that can be reduced is assessed, both quantitatively and qualitatively. The methodology and results of this estimation will be useful when building the life cycle inventory of construction materials and products for the Singapore construction industry. The lean benchmarking process provided in this study will be useful for the precast concrete industry to monitor carbon efficiency.

## **LEAN PRODUCTION PHILOSOPHY**

It is believed that lean production has its origin in the Toyota Production System (TPS), which was developed at Toyota by engineer Ohno. Ohno (1988) stated that the basis of the TPS is to achieve profit growth by reducing costs through completely eliminating waste such as excessive stocks and work force. The term “lean” was coined by the research team working on international automobile production to reflect both the waste reduction nature of the TPS and to contrast it with the craft and mass forms of production (Womack et al. 1990).

One of the first studies aimed at understanding and applying the lean production principles in the construction industry was carried out by Lauri Koskela in 1992 (Koskela 1992).

By applying the principles to the construction industry, Koskela identified the basis of the “new production philosophy”, which is also known in western countries as “lean production” (Isatto and Formoso 1998). Originated from the TPS, the core of the lean production philosophy is the observation that there are two aspects in all production systems: conversions and flows (Koskela 1992). Conversion activities refer to those which actually add value to the product or process. Flow activities refer to non-value adding activities, which consume time, costs and resources, but do not add value to the product or process. There are many interpretations about the lean principles. Koskela (1992) concluded eleven important principles which are essential to the lean production philosophy, such as reducing waste, variability, cycle and increasing transparency. Womack and Jones (1996) identified five principles about lean thinking and lean production, such as specifying value, identifying the value stream, etc. It should be noted that although the interpretations of the lean production philosophy may vary, four major points are all emphasized on:

1. Reduce non-value adding activities, such as maintaining inventory, multi-handling and multi-delivery, reproducing due to product defects, etc.
2. Produce according to customer requirements to prevent deviation costs.
3. Continually improve rather than to interpret the improvement processes as implementations that can be done once and for all.
4. Respect for humanity, which must be cultivated while the production system utilizes human resources to attain its cost objectives (Monden 1993).

Lean production is not a totally new concept. It is a combination of existing management philosophies in a new way. The most important tools in lean production include:

- Just-in-Time (JIT): The JIT concept was firstly initiated by Ohno and Shingo in Toyota to reduce and eliminate inventories. JIT means that in a flow process, the right parts needed in assembly reach the assembly line at the time they are needed and only in the amount needed (Ohno 1988).
- 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.
- Time based competition. Time based competition refers to compressing time throughout the organization for competitive benefit (Koskela 1992).
- Concurrent engineering. Concurrent engineering refers to an improved design process characterized by rigorous upfront requirements analysis, incorporating the constraints of subsequent phases into the conceptual phase, and tightening of change control towards the end of the design process (Koskela 1992).
- Value based management. Value based management refers to “conceptualized and clearly articulated value as the basis for competing” (Carothers and Adams 1991).
- Visual management. Visual management is concerned about visual control in production, quality and workplace organization (Greif 1991, p.281). By setting up a standard, any deviation from it will be recognized immediately. Thus, appropriate actions will be taken before damage happens.
- Total productive maintenance (TPM). Total productive maintenance refers to the autonomous maintenance of production machinery by small groups of multi-skilled operators (Nakajima 1988, p.166).

- 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).

The lean concept has proven to be effective in increasing environmental benefits by eliminating waste, preventing pollution and maximizing the owners' value (e.g. Huovila and Koskela 1998; King and Lenox 2001; Ferng and Price 2005; Lapinski et al. 2006; Nahmens 2009; Miller et al. 2010). Huovila and Koskela (1998) examined the contribution of the lean construction principles to sustainable development. The contributions included minimization of resource depletion, minimization of pollution and matching business and environmental excellence (Huovila and Koskela 1998). 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 the lean principles to a small furniture production company and found that the lean principles can help the company meet ever increasing customer demands while preserving valuable resources. 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 seems that the contributions were too broadly described. It should be noted that the contribution of the lean concept to a certain application area can guide the preferred decisions and behaviours of the precasters. If the contribution is defined too broadly, the implications for the precasters will be very minimal.

There were a few studies which argued that lean may show a negative impact on environmental performance (e.g. 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 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 that stakeholders hesitated to use the 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 factories to achieve low-carbon production.

## RESEARCH METHODOLOGY

### *Data Collection*

The purpose of this case study is to identify the non-value adding activities in precast concrete production from a lean perspective, examine how the lean concept can be applied to achieve low-carbon production and quantify the lean improvements. The subject of this case study is a precast concrete factory, which was set up in 1994 to spearhead the adoption of prefabrication technology in Singapore. A total land area of 17,000 m<sup>2</sup> and a built-up area of 21,000 m<sup>2</sup> were occupied. The main activities of the precaster included: 1) design and produce precast

concrete products; 2) manage and deliver precast concrete products; and 3) research on innovative construction materials. The precaster occupied large market share of the precast concrete market, especially in public housing projects. The production arrangements of the precaster would therefore reflect the general production practices in the Singapore precast concrete industry. As research played a very important role, the project manager in the precaster stated that several lean principles have been applied in the factory, which included the total quality control and continuous improvement.

To identify the non-value adding activities examined by the lean production concept in precast concrete production, a questionnaire was developed. The questionnaire encompassed a comprehensive list of all the non-value adding activities that might possibly occur in a typical precast concrete factory from a lean perspective. The list of non-value adding activities was obtained through literature review and semi-structured interviews that were conducted with seventeen precasters in Singapore. Semi-structured interview was requested with the project manager to identify the non-value adding activities that happened in the precast concrete factory. The project manager, who was also the senior executive engineer, has worked for the precaster for over 20 years. In addition, during the semi-structured interview, the probability of occurrence of the non-value adding activities was rated by the project manager. Unimportant non-value adding activities would be dropped from the assessment. A four-day site investigation was conducted to focus on the production process for a specific type of precast concrete column, which was chosen for the Life Cycle Assessment (LCA) study. LCA has been widely adopted to evaluate the environmental impact in both the manufacturing and construction sectors (Harris 1999; Petersen and Solberg 2002). It assigns elementary flows and potential environmental impact to a specific production system. In this study, the life cycle is limited to the production cycle of the precast concrete column and includes four value stages, which are site layout management, supply chain management, production management and stock management. During the site investigation, the embodied carbon of the precast concrete column was calculated based on the production procedure provided by the project manager. In addition, wastes, damages and energy consumption caused by the non-value adding activities were recorded for the following estimation process. The focus of the semi-structured interview and the four-day site investigation aim to address the following three questions:

1. Is the lean production philosophy applicable to the precast concrete production process to achieve low carbon production?
2. In current precast concrete production processes, what are the imperfections that can be improved to achieve sustainability?
3. How much carbon emissions can be reduced by applying the lean concept when producing this type of precast concrete column?

### **Data Analysis**

A general quantification procedure was developed for the precaster to calculate the lean improvements. The procedure included two major subprocesses, which were the screening process and the estimation process. There are three steps in the screening process, including:

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

**TABLE 1.** Information sources for materials, energy consumption and emission factors.

Materials, embodied carbon and energy consumption	Sources
Mix design of Portland cement concrete	Obtained from the precast concrete factory
Embodied carbon emissions of cement	Nisbet et al. (2000); Hammond and Jones (2008); Indexmundi (2006); U.S. Geological Survey (2006)
Embodied carbon emissions of aggregates	Hammond and Jones (2008)
Embodied carbon emissions of steel	World Steel Association (2008)
Carbon emissions from waterborne transportation	Department for Environment, Food and Rural Affairs (2005); McKinnon (2008)
Carbon emissions from road transportation	Peyroteo et al. (2007)
Energy inputs from concrete mixing plant	Nisbet et al. (2000)
Energy inputs from precast concrete factory	Observed and recorded in the precast concrete factory
Emission factor of electricity generation	National Environment Agency (2009)
Emission factor of idling trucks	Stodolsky et al. (2000)
Emission factor of illumination in the precast concrete factory	Recorded in the precast concrete factory

(Adapted from: Wu and Low, 2011a)

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. For example, carbon emissions caused by the use of equipment was calculated by multiplying the fuel consumption with the emission factor.
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 then provided.

The estimation process followed the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (Intergovernmental Panel on Climate Change 2008). The carbon emissions caused by fuel consumption is calculated by multiplying the fuel usage with the emission factor. Similarly, the carbon emissions caused by the use of electricity is calculated by multiplying the electricity usage with the respective emission factor. World-wide average emission factors from the database were used where Singapore-specific emission factors were not available. The emission factors used in the estimation process are obtained by referring to many other LCI studies. The LCI studies and information sources are shown in Table 1.

## RESULTS

### *The Embodied Carbon of the Precast Concrete Column*

The overall calculation of the embodied carbon of the precast concrete column is shown in Table 2. For this type of precast concrete column, 647.10 kg carbon emissions were generated in its production cycle (from cradle to gate). As can be seen from Table 2, the manufacture of steel seems to be the most significant source of carbon emissions, which accounts for 46.76%

**TABLE 2.** Embodied carbon of the specific type of precast concrete column.

Raw materials		Emission factors	Carbon emissions	
1. Cement	320.1300 kg	0.4970 kg CO <sub>2</sub> / kg	159.10 kg CO <sub>2</sub>	24.59%
2. Aggregates	540.6600 kg	0.0050 kg CO <sub>2</sub> / kg	2.70 kg CO <sub>2</sub>	0.42%
3. Reinforcement	178.0000 kg	1.7000 kg CO <sub>2</sub> / kg	302.60 kg CO <sub>2</sub>	46.76%
Energy inputs				
4a. Transportation (cement)(international)	320.1300 kg	104.2000 kg CO <sub>2</sub> / ton	33.35 kg CO <sub>2</sub>	5.15%
4b. Transportation (aggregate)(international)	540.6600 kg	121.6000 kg CO <sub>2</sub> / ton	65.74 kg CO <sub>2</sub>	10.16%
4c. Transportation (reinforcement)(international)	178.0000 kg	35.7000 kg CO <sub>2</sub> / ton	6.35 kg CO <sub>2</sub>	0.98%
5. Concrete plant operation	68.6000 kWh/m <sup>3</sup>	0.5233 kg CO <sub>2</sub> / kWh	25.52 kg CO <sub>2</sub>	3.94%
6a. Transportation (concrete)(local)	24.1500 km	0.1200 kg CO <sub>2</sub> / km / ton	9.77 kg CO <sub>2</sub>	1.51%
6b. Transportation (reinforcement)(local)	24.1500 km	0.1200 kg CO <sub>2</sub> / km / ton	1.03 kg CO <sub>2</sub>	0.16%
7. Precast concrete production	6.5000 kWh	0.5233 kg CO <sub>2</sub> / kWh	3.40 kg CO <sub>2</sub>	0.53%
			<b>Total</b>	609.58 kg CO <sub>2</sub> 94.20%
8. Waste of raw materials—2%			9.29 kg CO <sub>2</sub>	1.44%
9. Waste of finished products—3%			18.29 kg CO <sub>2</sub>	2.83%
10. Inefficient production arrangements			9.93 kg CO <sub>2</sub>	1.53%
			<b>Total</b>	647.10 kg CO <sub>2</sub>

(Adapted from: Wu and Low, 2011a)

of the total carbon emissions generated. Attention should be paid to the production process in the precast concrete factory. It seems that production processes only account for 0.53% of the total carbon emission generated. However, in the precast concrete production process, waste of raw materials, waste of finished products and inefficient production arrangements often happen and contribute to increase the level of carbon emissions. The three aspects are examined in each of the four value stages of the precast concrete production, which are site layout management, supply chain management, production management and stock management.

### **Site Layout Management**

The non-value adding activities identified in the questionnaire were rated based on two factors, which were the probability of occurrence and the impact on the level of carbon emissions. It should be noted that although the non-value adding activities relating to the raw materials seems to be irrelevant to site layout management, it is analyzed in this section due to its higher priority than those other activities listed in the value stages later (supply chain management, production management, etc). The specifications of the raw materials and the design of the precast concrete products should be completed before deliveries and production activities are arranged. Following the screening procedure, the less important factors are dropped from the

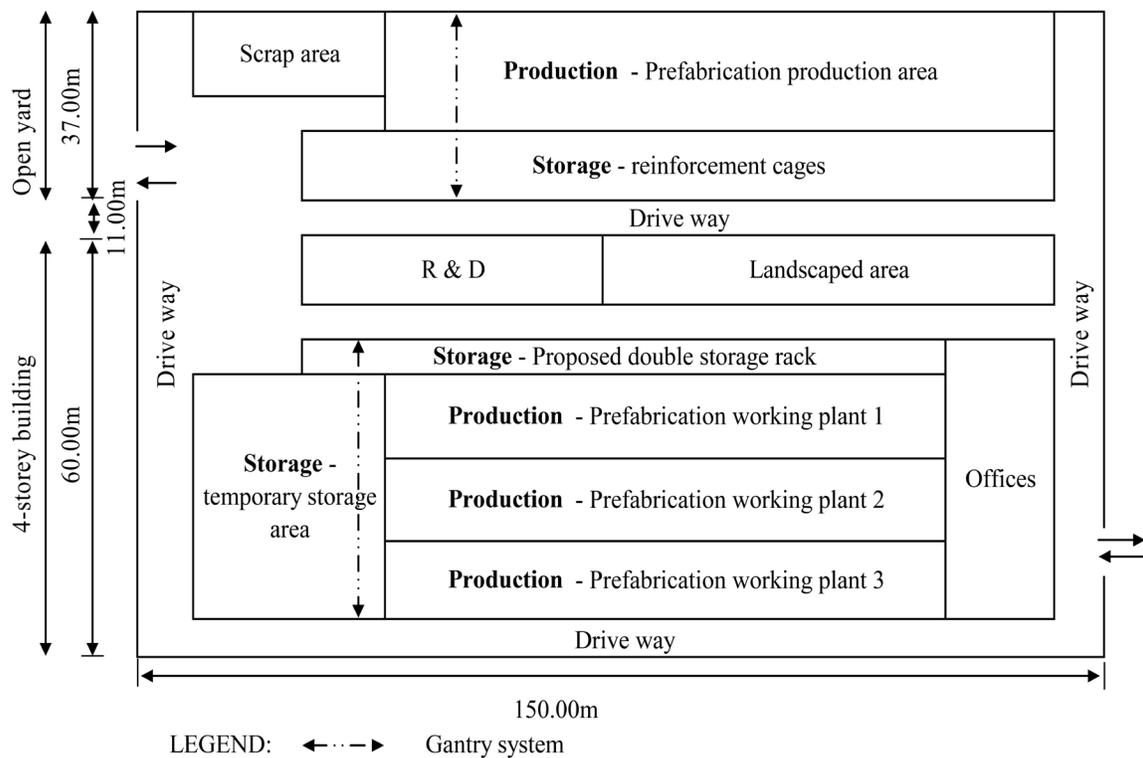
estimation assessment. The precaster appeared to face several problems in site layout management, which included:

*Improper specifications of building materials.* According to the project manager interviewed, changes to the specifications of precast concrete products happened occasionally. Due to the changes, the process to design and produce such precast concrete products had to be re-developed. The previously manufactured products would therefore no longer be used. It was a waste of both raw materials and energy consumption and such change of specifications should be eliminated. Based on one previous experience of such change, six precast concrete columns have been produced and abandoned due to change of specifications in the contract period, which is half a year.

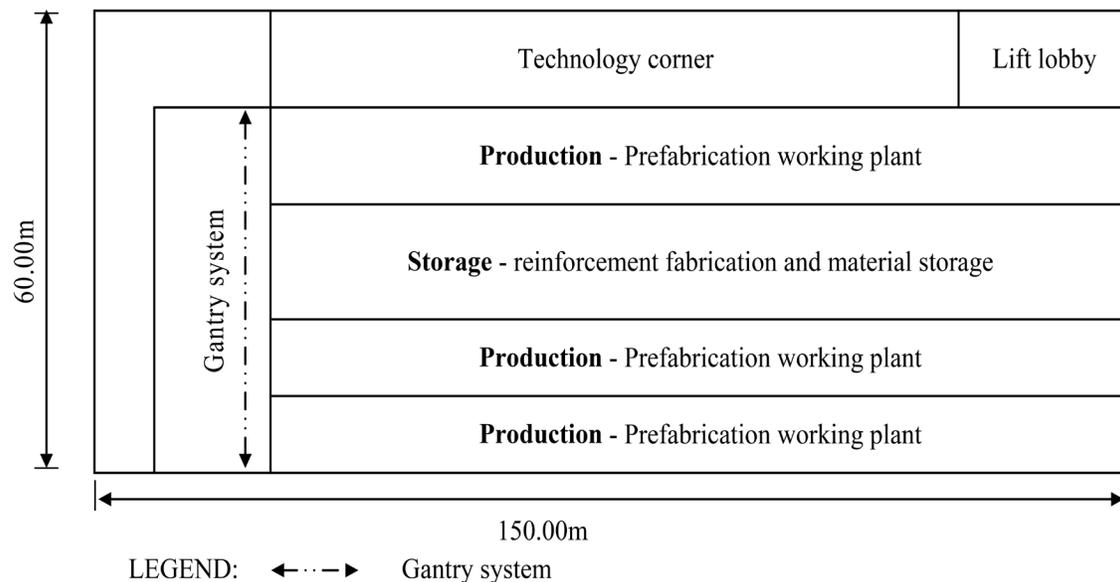
*Over provision for material storage.* The site layout plans are shown in Figure 1 and Figure 2. A 4-storey building and an open yard were included in the site layout plan. The storage of the finished products is within the production yard. The material storage area occupies 26.4% of the total area in the site layout design. The total storage area (including storage for finished precast concrete products) is about 40.0% of the total area when the storage of the finished products was considered as well.

Large storage can lead to unnecessary loading and unloading activities, such as singling out and transferring activities. The singling and transferring activities were conducted by the gantry system and trailers. As the precast concrete columns were produced in the prefabrication production yard of the open yard, as shown in Figure 1, singling out and transferring activities happened in this area were chosen for estimation.

**FIGURE 1.** The site layout design of the ground floor.



**FIGURE 2.** The site layout design of the 2nd, 3rd and 4th floor of the 4-storey building.



In addition, waste of either raw materials or finished products during inventory could happen due to such a large storage area. According to the project manager interviewed, there was a 2% wastage of raw materials and a 3% wastage of finished products.

*The site layout was not carefully planned to achieve economic and efficient production.* Although the precaster claimed to have an economic and efficient site layout design, the site layout was not designed to be lean. As can be seen in Figure 2, the reinforcements delivered from suppliers were sent to the 2nd and 3rd floor of the 4-storey building for fabrication. When the fabrication was completed, reinforcement cages were then delivered to the storage area in the open yard. Singling out and transferring activities were caused by placing the storage area on the 2nd and 3rd floor. On the other hand, damages to raw materials might also happen due to such arrangements.

*Green building materials were not considered.* The precaster stated that research related to new green building materials was followed but rarely applied. For example, according to Nielsen (2008), reducing the clinker content by substitution with supplementary cementitious materials such as fly ash has a dramatic impact on the carbon footprint of the concrete. According to Prusinski et al. (2006), carbon emissions savings for precast concrete ranges from 147 to 222 kg/m<sup>3</sup> if slag cement mixtures were adopted. In fact, the savings of carbon emissions for concrete with 28-day compressive strength of 5,000 psi (which is similar to the concrete used in this study) are 147 kg/m<sup>3</sup>, if 50% of the Portland cement is replaced by slag cement. Compared with 100% Portland cement mixtures, this will produce a savings in carbon emissions of 24.11% for the precast concrete columns. However, only regular cement (Portland cement) was adopted in current precast concrete production. Unless the willingness to use such green materials was expressed by clients, green building materials were not usually adopted.

*Site layout plan was not placed on the notice board for information.* On the notice board of the precaster, safety issues were emphasized, as well as the provision of a detailed contact list. The amount of information was not sufficient to support a smooth production flow. Examined by the visual concept in the lean production philosophy, the information on the notice

board should be sufficient and transparent. Two important aspects should be displayed on the notice board, which are waste streams and logistics of daily production (Blumenthal 2008). By doing so, the lead time can be reduced, thus reducing the costs.

### **Supply Chain Management**

Similar to the site layout management, there were a few non-value adding activities in the supply chain management which might cause an increase in the level of carbon emissions.

*Large quantity supply base.* Large quantity supply base could lead to large storage area and cause the same problems identified in the section of site layout management. An amount of 0.58kg CO<sub>2</sub> per column was emitted by singling out and transferring activities. In addition, as can be seen in Figure 1 and Figure 2, a total of 3,672 m<sup>2</sup> covered storage area was provided. Energy consumption due to illumination can be saved if the storage area is reduced by applying the lean concept.

Advance orders for raw materials should be placed weeks before the actual delivery date for the precasters to organize their production processes so that the precast concrete products can be delivered immediately to the construction sites when produced, thus reducing carbon emissions in the storage and singling-out processes. In addition, Ballard et al. (2003) proposed a decoupling buffer between pre-manufacturing and manufacturing to reduce inventory. According to Ballard et al. (2003), the customer orders (which is the advance orders mentioned earlier) were made ready to project schedules, but were manufactured in response to project call offs (which are confirmation orders) received one week prior to needed delivery. By using the decoupling buffer, values are generated for both customers and producers and wastes are eliminated.

*No long-term contract to achieve loyalty between suppliers and precasters.* Long-term contract between suppliers and precasters may help to reduce the number of delivery and servicing trips, reduce trips in peak hours and reduce waste (Evanson 2008). When such relationship was built, precasters might ask the suppliers to hire operators with high awareness of sustainability in terms of certification programmes (e.g. the Freight Operator Recognition Scheme in the UK). These benefits could help reduce carbon emissions but could not be assessed in this case study because it involved a long-term monitoring process which could not be completed given the time constraint.

*Transportation was not taken into consideration.* Price structure was the main consideration when selecting suppliers. By doing so, precasters lost control of the delivery. Of all the delivery methods provided, only direct delivery was adopted in this case. If other lean delivery methods were adopted, such as milk round collection and delivery with an interposed warehouse, precasters would have more control on the arriving time of the delivery, thus reducing the lead time. In fact, if the precaster was using his own transportation trailer and the return trip is fully utilized, a carbon reduction of 0.58 kg CO<sub>2</sub> per column can be achieved for steel transportation. Since concrete transportation required the use of in-transit mixers, the return trip for concrete might not be utilized at the moment.

### **Production Management**

The production process of precast concrete columns involved the use of the gantry system and some other equipment. Due to the involvement of the equipment, facilities managers and operators should have the greatest potential to reduce energy consumption and carbon emissions. There were several types of non-value adding activities that were observed in the factory.

*Waste of raw materials and damages of raw materials.* Both factors led to the 2% wastage of raw materials, as mentioned earlier, which increased the level of carbon emissions level by an amount of 9.29 kg per column.

*Raw materials did not meet specifications.* According to the project manager interviewed, re-order and re-delivery of raw materials happened occasionally due to unsatisfied quality. During the contract period, two re-deliveries occurred. Two subsequent arrangements for local transport of concrete and steel should therefore be arranged. A total amount of 0.47 kg CO<sub>2</sub> per column was generated for each precast concrete column.

*Unnecessary materials handling.* When observed in the precast concrete factory, it was found that the employees lacked the awareness about the importance of a smooth work flow. For example, when the gantry operator intended to pick up the reinforcement cage for placing and had moved the gantry to a specific location, he was asked to carry out the lifting process in another location. This unnecessary movement was caused by incompetent employees and the lack of a written production manual. During the four-day observation, this unnecessary movement happened three times and it was assumed that this frequency remained during the contract period. Potential damages to raw materials could also be caused by such unnecessary materials handling.

*Wait time.* The two most important categories of wait time in this case were wait time for inspection and wait time for labor. When the finished precast concrete products were placed on the trailer and the quality control checks were conducted, the trailer was left idling. When the trailer driver was handing the paper work to the supervisors, the trailer was left idling as well. A total time of six minutes were recorded. According to the American Trucking Association (1998), if a truck was left idling for one hour, an amount of 10.397 kg CO<sub>2</sub> would be emitted. North Carolina's Environmental Management Commission has adopted a rule to restrict on-road gasoline and diesel-powered vehicles with a loaded weight greater than 10,000 pounds from idling for more than 5 consecutive minutes in any 60-minute period (U.S. Department of Energy 2010). According to the U.S. Department of Energy (2010), Rhode Island also restricts the vehicle from idling for no more than 5 minutes by law. These regulations validate the important of managing the wait time in order to achieve low carbon emissions.

*Double-handling or delivery due to unsatisfied quality or specifications.* According to the project manager interviewed, double-handling due to quality problems happened occasionally in the demoulding and lifting process. For precast concrete columns, sockets and anchors were often used. The connection between the sockets and anchors and the concrete was very strong in some cases that double-handling was necessary. This was very common in the production of precast concrete columns, although each release might need different degree of effort.

Wrong deliveries due to unclear identification marks or unclear delivery notes did happen previously, although in an extremely low frequency of once or twice a year. It was assumed that one wrong delivery happened in the contract period with the delivery of six precast concrete columns. A total of 32.41 kg CO<sub>2</sub> was generated by the wrong delivery.

*Inadequate work crews, weak employees and lack of supervision.* The precaster stated that the competency of both employees and supervisors could be improved. If such improvements could be achieved, the waste of raw materials and finished products, as well as the non-value adding activities could be eliminated.

## Stock Management

Stock management represents the fourth value stage in the overall production cycle in the precast concrete factory. Time and energy will be consumed when building up inventory and singling out the products for delivery. Inefficient stock management will therefore obstruct the production process from being efficient and sustainable. Three types of non value adding activities were observed in the factory.

*Inefficient staffing arrangement.* A crane driver, a banksman and a charge-hand should be provided in the precast concrete factory to carry out lifting process. However, this was not always followed. As observed in the factory, when moving the precast concrete columns to the storage area, the gantry operator was doing all the work. A lot of sudden accelerating and braking were caused when only one person was involved to conduct the loading and unloading activities. Sudden accelerating and braking would cause an increase in the level of carbon emissions and might damage the precast concrete products.

*Unclear identification marks and unclear delivery notes.* According to the project manager interviewed, wrong deliveries happened in an extremely low frequency of one or two times a year. It was assumed that two wrong deliveries, one under each category, happened in the contract period. An amount of 0.14 kg CO<sub>2</sub> per column was generated due to the wrong delivers. It should be noted that delivery of the finished products does not fall within the boundary of “cradle to gate” and should not be considered in this study. However, this does not mean that the management of correct delivery is not important. On the contrary, clear identification marks and delivery notes should be provided to ensure that the right precast concrete products are delivered to the right construction site at the right time.

*Lack of sufficient care.* The precaster stated that with sufficient care, waste of finished products and wrong delivery could be avoided. In fact, operators who were closely related to facilities operations have the greatest potential to reduce energy consumption and carbon emissions. However, the training programmes provided to the operators were currently not sufficient to support sustainable operations and needed to be improved.

## DISCUSSIONS

### Lean and Low-Carbon Production

The amount of carbon emissions that can be reduced by applying the lean production philosophy is shown in Table 3. A few implications could be inferred from Table 3 and Table 2.

Effective carbon can be calculated when there is no waste in the production process. This is the embodied carbon of the precast concrete column when all production processes are value-adding to the product. As shown in Table 2, 94.20% of the carbon emissions value of the precast concrete column is generated through value adding activities. A total amount of 37.51 kg CO<sub>2</sub> (5.80%) was emitted in terms of waste of raw materials, waste of finished products, and inefficient production arrangements. Another 13.11 kg CO<sub>2</sub> (2.03%) could be reduced if the precast concrete factory was designed with no inventory of raw materials. The amount of carbon emissions that can be reduced by applying the lean concept in the factory was 7.83%. This amount of carbon emissions was in fact obtained through a lean benchmarking process which can help the precaster to improve towards low carbon emissions. It is recommended that this process is provided along with the LCA study to provide a long-term benchmark to identify the potential improvements that precasters can achieve.

**TABLE 3.** Non-value adding activities identified in the production process.

Category	The amount of carbon emissions (kg CO <sub>2</sub> /column)
<b>Waste of finished products</b>	<b>18.29</b>
Too much inventory in factory	
Damaged products during inventory	
Damaged products when handling	
Double-handling or delivery due to unsatisfied quality or specifications	
<b>Illumination savings</b>	<b>13.11</b>
Over provide material storage	
Large quantity supply base	
Too much inventory in factory	
<b>Waste of raw materials</b>	<b>9.29</b>
Over provide material storage	
The site layout is not carefully planned to achieve economic and efficient production	
Waste of raw materials in the production process	
Materials damaged during handling	
Unnecessary materials handling	
<b>Inefficient production arrangements</b>	<b>9.93</b>
Improper specification of building materials	7.25
Over provide material storage	0.58
The site layout is not carefully planned to achieve economic and efficient production	0.96
Transportation is not taken into consideration	0.58
Raw materials do not meet specifications	0.47
Unnecessary materials handling	0.0030
Double-handling or delivery due to unsatisfied quality or specifications	0.09
<b>Delivery performance</b>	<b>0.14</b>
Unclear identification marks	0.07
Unclear deliver notes	0.07
<b>Other qualitatively described lean improvements</b>	Please refer to the qualitative assessment for each factor
Does not think of green building materials	
Site layout is not placed on the notice board for information	
No long-term contract to achieve loyalty between suppliers and contractors	
Transportation is not taken into consideration	
Human resources	
Inefficient staffing arrangement	
Lack of sufficient care	

(Source: Wu and Low, 2011b)

It seems that there are three possible strategies to reduce the carbon emissions of precast concrete production. One strategy is to reduce the effective carbon by using fewer raw materials. This could be achieved by developing alternative designs and using green building materials. As stated earlier, a savings in carbon emissions of 24.11% for the precast concrete column can be achieved, if 50% of Portland cement is replaced by slag cement. Other than countries with local supplies of raw materials (e.g. China, the U.S.), the production of precast concrete columns in Singapore relies heavily on the import of raw materials. As can be seen in Table 2, international transport of raw materials accounts for 16.29% of the total embodied carbon emissions. If the precast concrete columns are produced in countries with local supplies of raw materials, the carbon emissions value can be significantly reduced. This represents another strategy for the precasters to reduce carbon emissions by ordering regionally manufactured materials. Precasters can also focus on reducing waste of raw materials, waste of finished products and inefficient production arrangements to reduce carbon emissions. The third strategy is especially important when green building materials are used and the embodied carbon of the precast concrete products is reduced. Delivery and operation activities play a more important role when the carbon emissions from raw materials are reduced. Some precasters preferred to locate the concrete plant within the factories. It should be noted that this poses new challenges to the precasters to simultaneously manage the production processes of both the concrete and the precast concrete products. Because of the overlapping of production processes of the concrete and the precast concrete product, waste of raw materials, finished products and inefficient production arrangements may happen more frequently when such a production strategy is adopted, although an economic savings can usually be garnered therefrom.

Wait time for inspection and labour should be especially noted here because delivery is the link between precasters and contractors. The trailer drivers were not appropriately trained on the awareness of sustainable operations. It is therefore reasonable to assume that equipment idling might happened in delivery and when unloading at construction sites. Precasters should therefore take concrete steps to stop vehicles from idling. For example, a notice board should be placed at the entrance of the factory to remind the driver to turn off the engine while waiting at the site. As stated earlier, the North Carolina's Environmental Management Commission and some other states in the U.S. are taking actions to reduce equipment idling by enacting regulations and restrictions. It appears timely for Singapore to take steps to develop similar law to raise operators' awareness on sustainable operations.

Different precasters might face different non-value adding activities. The precaster was a leading government-sponsored entity who might have better environmental performance than other precasters in Singapore. The amount of carbon emissions that can be achieved by applying the lean production philosophy for other precasters might be larger than the case study provided in this paper.

### ***Lean Benchmarking and Its Application to Construction Materials***

Carbon labelling programmes (usually included in environmental labelling programmes) can offer accurate estimation of the embodied carbon of construction materials by using LCA techniques. It should be noted that only production cycle is considered in this research adopting the "cradle-to-gate" concept. However, it lacks a benchmark to identify how efficient the production is. There should be two levels of benchmarking, which are short-term and long-term benchmarking. Current carbon labelling programmes can offer a short term benchmark

between different precasters. The comparison can be intuitively interpreted by the scores obtained from the carbon labelling programmes. Consumers can therefore obtain the products' carbon performance through such scores. However, the long term benchmark is currently missing for construction materials, or at least in the precast concrete sector. In other words, a lean benchmark which may represent tomorrow's world class company is not provided for comparison at all. In this case, when all the non-value adding activities are eliminated, a total amount of 609.59 kg CO<sub>2</sub> is emitted per precast concrete column, which can be transferred to 1.77 ecopoints under the UK Ecopoints scheme, while the actual score is 1.88 ecopoints. 0.11 ecopoints can be saved by applying the lean concept. It should be noted that illumination savings and delivery performance of the finished products are not within the boundary of the LCA in this study. The carbon emissions from the two sources are calculated but not discussed. However, potential improvement that can be achieved by applying the lean concept can be predicted from the calculation.

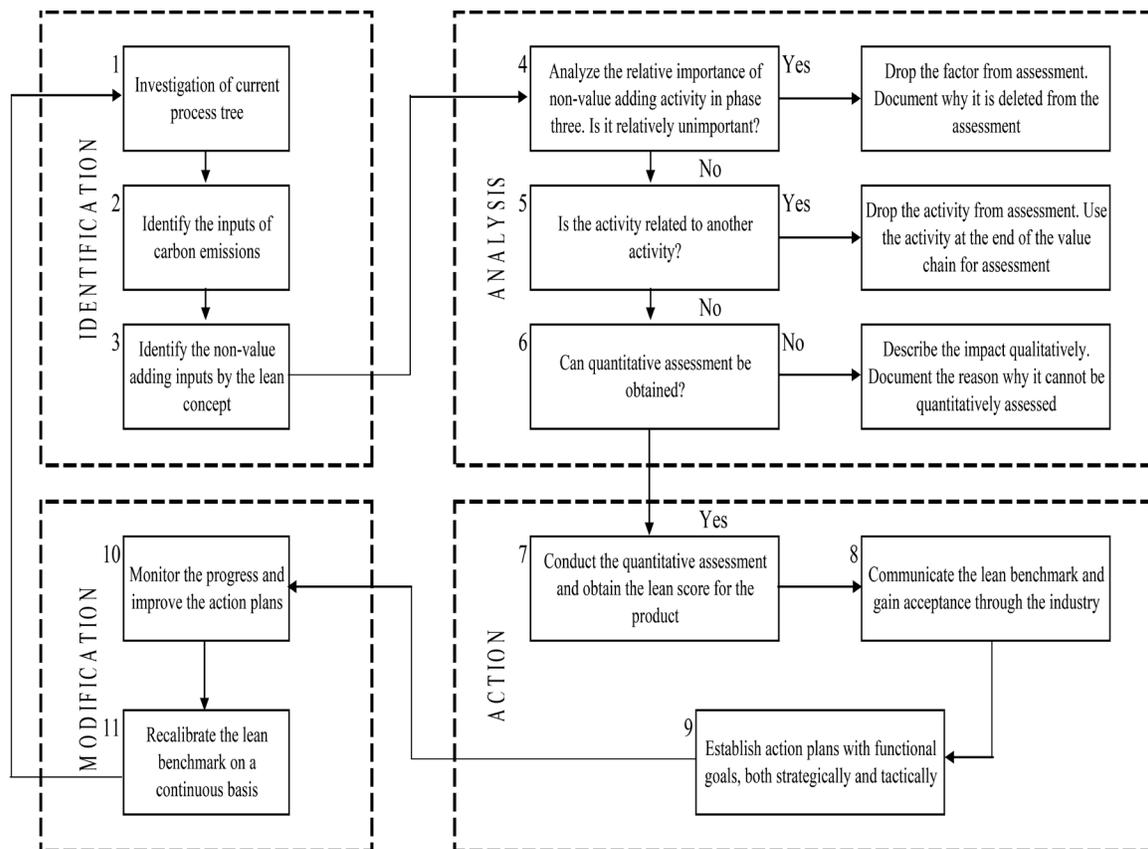
Unlike normal carbon labelling programme which highlights the inputs and outputs of resources and energy by design specifications, this lean benchmark advocates issuing the carbon label based on a refined production process. In practice, it is recommended that a lean score is provided, associated with the carbon score obtained from the carbon labelling programme. This lean score represents the carbon efficiency of the product. In this study, the 0.11 ecopoints is the lean score when the production process is refined.

When issuing the lean score for the precast concrete products, there are several areas that should be considered. First, the efficiency of current production compared to the leanest case where all the non-value adding activities are eliminated should be calculated. This is designed to address the problem that LCA has little to say about the potential of the systems (Grant and Macdonald 2009). Secondly, a score should be assigned to new innovative technology, which may fare poorly in the LCA rating, but can bring potential benefits to the environment in the future. In addition, production processes with "continuous improvement" plans should have better scores than those without such plans. This offers a long-term view in the benchmarking process. Otherwise, both production processes with and without the "continuous improvement" plans will be issued with the same score under normal carbon labelling programmes, where the limits and risks of the production systems are not reflected at all.

The applicability of the lean benchmarking process in carbon labelling programme for precast concrete products can therefore be summarized into the four phases, as illustrated in Figure 3:

1. Identification. In this phase, the production process tree is refined by lean to identify the true valuable inputs. Non-value adding activities are identified and eliminated in order to provide the lean benchmark.
2. Analysis. Carbon emissions that can be reduced by eliminating the non-value adding activities identified in phase one is calculated. Both quantitative and qualitative method should be adopted. For non-value adding activities which involve the use of energy consumption and raw materials, quantitative calculation should be provided. On the other hand, for evaluating the impacts that are difficult to quantify (e.g. continuous improvement and top management commitment), qualitative evaluation of the impacts should be conducted.
3. Action. A corresponding long-term benchmark associated with the lean score should be obtained in this stage to provide a relative measurement about the efficiency of the

**FIGURE 3.** Lean benchmarking process in carbon labelling programmes.



- materials towards environmental sustainability. A “continuous improvement” plan to help the materials to improve towards the long-term benchmark should be prepared as well.
4. **Modification.** As technology improves and the production process refines, the lean score calculated in phase 3 may change. Recalibration of the lean benchmark on a continuous basis is therefore proposed in this stage to offer up-to-date information for customers.

In an industry as complex as construction, a wide range of raw materials are used, many in a number of different applications, during the erection of a building or structure (Construction Industry Research and Information Association 1995). The lean benchmarking process is firstly designed for precast concrete products because of the origin of the philosophy from the manufacturing industry. Lean production philosophy originated from the automobile industry and has been applied in the manufacturing industry for decades. The production process of precast concrete products has many similarities with the manufacturing industry so that the application of lean in the precast concrete industry will require less modifications of the lean concept.

However, the origin of the lean concept does not preclude applying the lean concept to the carbon labelling programmes of other construction materials, because:

1. The production process of construction materials can be viewed as a manufacturing process. According to Groover (2010), manufacturing is the transformation of materials into items of greater value by means of one or more processing and/or assembly operations. In fact, according to Groover (2010), the terms production and manufacturing can be used interchangeably. The construction materials industry belongs to the secondary manufacturing industry which uses natural resources and transforms them into consumer and capital goods.
2. Viewed as manufacturing process, the production of other construction materials are very similar to the production of precast concrete products. Construction Industry Research and Information Association (1995) identified the life cycle of construction materials into three stages: production, in-service use and after-use. Production includes the extraction of raw materials, storage, transportation, process and packaging, all of which are very common in the production of both precast concrete products and other construction materials.
3. The carbon labelling programmes designed for precast concrete products and other construction materials are the same, using LCA as the evaluation approach. Therefore, the carbon labelling programmes for other construction materials may face the same problems caused by LCA, such as the lack of evaluation about the limits, risks and potential of the production systems.

The lean concept is appropriate to address the problems caused by LCA to the carbon labelling programmes of construction materials other than precast concrete products. A production tree can still be obtained and refined, based on which a lean score can be calculated. With both the carbon score and the lean score, the true environmental performance of the products can be indicated more transparently and accurately.

## CONCLUSIONS

With the rising global recognition of sustainable development, it is only a matter of time when pressing sustainability regulations fall on the precasters to improve their environmental performance, such as reducing energy consumption and carbon emissions. When examined by the lean production concept, the whole value chain of precast concrete production can be improved by reducing many activities that do not add value to the production process. Carbon emissions due to waste of raw materials, waste of finished products, inefficient production arrangement and capital facilities can be reduced if such non-value adding activities are eliminated. Unlike technical improvements and innovations to achieve sustainability which can be costly, the application of the lean production concept is in fact a series of management practice improvements that do not involve high investment costs and will be able to help precasters to achieve better performance and environmental sustainability.

In accordance with previous studies, it is found that many lean techniques have been adopted in precast concrete production, such as the total quality control concept, pursuing zero defect products, etc. However, the applications are made to address specific problems that happen in precast concrete factories rather than the fundamental problems that cause the production imperfections. It is proposed that the value chain of precast concrete production should be examined when applying the lean techniques to address a specific issue, such as the sustainability issue in this study. However, it should be noted that the production processes of

different precasters vary and further case studies validating the replicability of the case should be investigated.

In addition, it is found that the lean production philosophy can provide a lean benchmark for precast concrete products, as well as other construction materials. It can help the precasters to monitor the carbon efficiency of the production processes. By obtaining this level of information in the carbon labelling programmes, contractors and developers can choose the truly environment-friendly materials and the construction industry can then move towards being a low carbon industry.

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