

# Lean production, value chain and sustainability in precast concrete factory - a case study in Singapore

Wu Peng<sup>1</sup> and Low Sui Pheng<sup>2</sup>

## Abstract

**Research Question:** Is the lean production philosophy applicable in precast concrete factories to achieve sustainability? If it is, what are the imperfections that can be improved to achieve sustainability?

**Purpose:** This study aims to identify the contribution of the lean concept to achieve sustainability in precast concrete factories. By using appropriate lean principles, the precast concrete industry can move closer towards sustainability.

**Research Method:** Quantitative assessment of each non-value adding activity is provided. Qualitative descriptions are provided for activities that cannot be assessed quantitatively.

**Findings:** The results indicate that the value chain in precast concrete factories has the potential to improve. Carbon emissions can be reduced in precast concrete factories to achieve low-carbon production.

**Limitations:** Precast concrete products are investigated in this study, which may limit the applicability of this study to other construction materials. Further researches are suggested.

**Implications:** The lean production philosophy has practical contributions to sustainable development, which can be adopted by precasters to achieve better performance in some sustainability factors, such as energy consumption, carbon emissions as well as production efficiency.

**Value for practitioners:** By eliminating the non-value adding activities identified in this study, precasters can achieve more environment-friendly and efficient production. In addition, regulatory bodies may initiate a lean benchmark for the precasters to identify how efficient current production is, as well as for the consumers to choose truly environment-friendly construction materials.

**Keywords:** Sustainable development; Precast concrete; Lean production; Value chain

**Paper type:** Case Study

---

<sup>1</sup> Ph.D. Candidate, Department of Building, 4 Architecture Drive, National University of Singapore, Singapore 117566. g0700346@nus.edu.sg

<sup>2</sup> Professor, Department of Building, 4 Architecture Drive, National University of Singapore, Singapore 117566. bdglowsp@nus.edu.sg



## Introduction

Sustainable development is usually defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987, p.43). Due to the rising recognition of sustainable development, 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 consumed 36 percent of the total energy used, 30 percent of the raw materials used and 12 percent of potable water consumed in the USA. Construction companies are encouraged to take environmental considerations into their daily decision making process. Regulatory bodies, both international and national, keep imposing pressures on construction companies to invest in low energy consumption and environment-friendly techniques. For example, the United Nations Framework Convention on Climate Change (UNFCCC) was founded in 1992 to deal with the global climate change. The Kyoto Protocol was established to set binding targets for industrialized countries to reduce carbon emissions by the year 2012 (Yates, 2007). In Singapore, by acceding to the Kyoto Protocol, the National Climate Change Committee was formed in 2001 to cover climate change in its scope, which has already included energy efficiency and renewable energy.

Precast concrete products are widely adopted in the Singapore construction industry due to the rising demand from public housing projects. One of the solutions to reduce construction duration and improve efficiency would be to use precast concrete products which are able to provide a cost-effective way of carrying out “system building” types of construction projects. Herrmann et al. (2008) proposed that besides classical economical production objectives (e.g. cost, time and quality), environmental driven objectives (e.g. low CO<sub>2</sub> emissions) should be considered in the production process. Due to the rising recognition of global climate change, the term “CO<sub>2</sub> emissions” is often used as one environmental sustainability indicator for the products. This research therefore aims to apply the lean production concept in precast concrete factories. The main objectives of this study are: 1) to highlight the link between the lean concept and sustainable development; 2) to examine the contribution of lean to a few sustainable management practices; and 3) to investigate the contribution of lean when assessing environmental values.

## Lean and the environment

Originating from the Toyota Production System, the lean production philosophy is developed as a way of thinking which advocates reducing or eliminating non-value adding activities as well as improving the efficiency of value adding ones at the same time. The lean philosophy can be considered as a new way to design and make things that are differentiated from mass and craft forms of production through the objectives and techniques applied on the shop floor, in design and along supply chains (Howell, 1999). There are many interpretations about the core of the lean production philosophy. Koskela (1992) concluded eleven important principles which are essential to the lean philosophy, such as reducing waste, variability, cycle and increase transparency. Womack and Jones (1996) identified five principles about lean thinking and lean production, including specifying value, identifying the value stream, etc.



Due to the rising recognition of the environmental impacts, more and more research has been conducted to develop and explain the value of the environment, which is usually referred to as environmental values. Many people argued that the environment does not only have instrumental values (i.e. to provide support to human beings), it has intrinsic moral values (Callicott, 1984, 1986, 1995; Rolston, 1988; Nash, 1989; Norton, 1991). According to Satterfield (2001), even if due to consciousness, only humans are moral agents (and thus can evaluate things), that is not to say that ecosystems, organisms and species are not morally good or possess certain kinds of value in and of themselves. The argument of the value of the environment has developed into a research area, which is referred to as environmental ethics.

The normally recognized values in the construction industry are quality, time and cost. Kaplan and Norton (1996) proposed a balanced scorecard to understand how buildings add value to clients. There were four aspects in the scorecard: financial value, indoor environmental quality, spatial quality and symbolism. Winch (2002) developed a new process based on Porter's value system concept (Porter, 1985) to capture of value generated through the project life-cycle - in terms of both profits and learning. More and more researchers started to include the environment as one more pillar of values of the buildings (Ofori, 1992;; Huovila and Koskela, 1998; Lapinski et al., 2006).

The lean concept has proven to be effective in increasing environmental benefits by eliminating waste, preventing pollution and maximizing the owners' value (Huovila and Koskela, 1998; Riley et al., 2005; Ferng and Price, 2005; Luo et al., 2005; Lapinski et al., 2006). Huovila and Koskela (1998) examined the contribution of the lean construction principles to sustainable development. The contributions include minimization of resource depletion, minimization of pollution and matching business and environmental excellence (Huovila and Koskela, 1998). EPA (2003) found that lean produces an operational and cultural environment that is highly conducive to waste minimization and pollution prevention, and that lean provides an excellent platform for environmental management tools such as life cycle assessment and design for environment. Luo et al. (2005) applied the lean concept to prefabrication and stated that lean can contribute to improve quality and supply chain and reduce waste. Bae and Kim (2007) found that different lean applications may have different results on the three pillars of sustainable development (i.e. economic, social and environmental sustainability). For example, lean supply may have influence on economic and environmental impacts rather than social impacts. Nahmans (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 (Nahmans, 2009).

## Research methodology

To identify current non-value adding activities examined by the lean production concept in precast concrete production, a questionnaire including the non-value adding activities in the precast concrete production processes was developed. 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 of Precaster A. In addition, a four-day site investigation was conducted in Precaster A to focus on the production process for a



specific type of precast concrete columns. The focus of the interviews and site investigation aim to address the following three questions:

1. Is the lean production philosophy applicable in precast concrete production to achieve low carbon production?
2. What are the contributions of the lean concept to the sustainable development practices?
3. How can the lean concept be used to improve the assessment of environmental values?

A general procedure was developed for Precaster A to calculate the lean improvements. The procedure included two major subprocesses, which were the screening process and the estimation process. In the screening process, the non-value adding activities that only happened in Precaster A were chosen for examination following a Value Stream Mapping (VSM) method. A value stream is a collection of all actions (value added as well as non-value added) that are required to bring a product (or a group of products that use the same resources) through the main flows, starting with raw material and ending with the customer (Rother and Shook, 1999). VSM aims to identify all types of waste in the value stream and to take steps to try and eliminate these by the following steps (Rother and Shook, 1999):

1. Choose a particular product as the target for improvement (Abdulmalek and Rajgopal, 2007). In this case study, a type of precast concrete column is chosen as the target for improvement.
2. Draw a current state map that is essentially a snapshot capturing how things are currently being done (Abdulmalek and Rajgopal, 2007). The production process of the precast concrete column is therefore investigated in order to generate the value chain.
3. Identify the non-value adding activities in each value stage.

When the non-value adding activities in Precaster A are identified, the estimation process is conducted to quantify the carbon emissions that can be reduced by applying the lean philosophy. The importance of the non-value adding activities in Precaster A was identified. Activities with no probability of occurrence or little importance were dropped from the assessment. Quantitative assessment for each non-value adding activities was preferred. The emission factors were obtained by referring to a series of other LCI studies, as shown in Table 1. However, qualitative descriptions of the impact of such non-value adding activities to the level of carbon emissions could be provided when such activities were not eligible for a quantitative assessment.

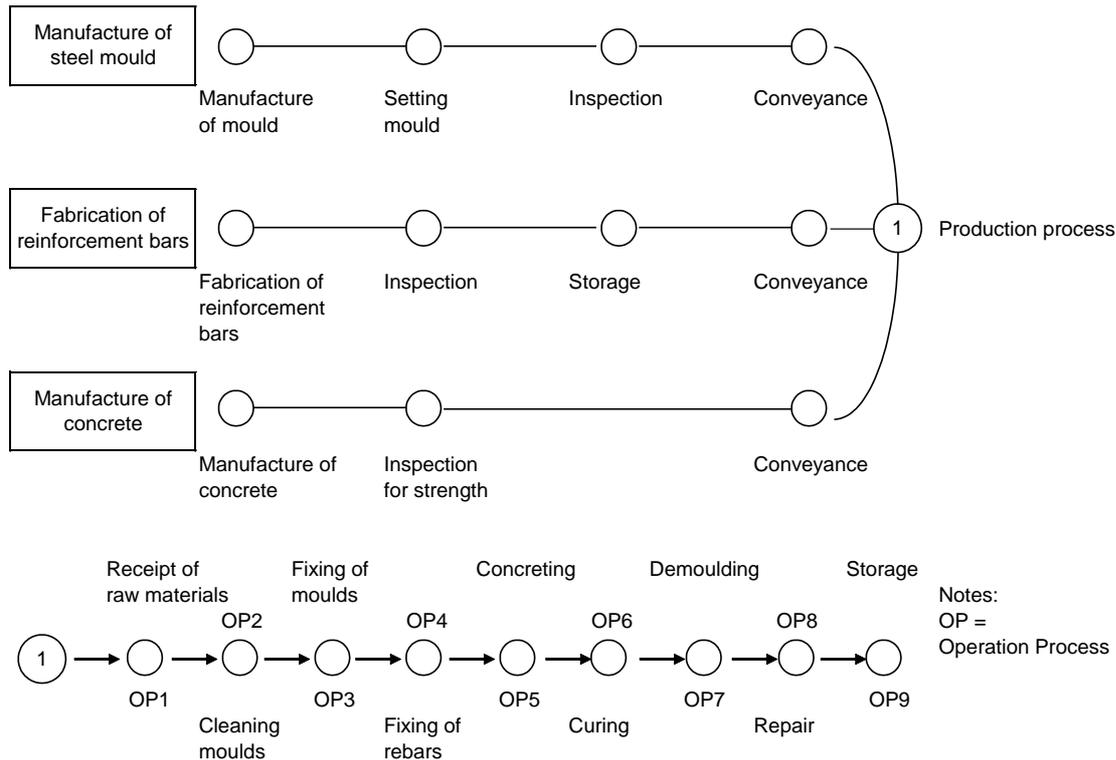
**Table 1 Information sources for materials, energy consumption and emission factors**  
(Source: Wu and Low, 2011)

Materials, embodied carbon and energy consumption	Sources
Mix design of portland cement concrete	Obtained from precast concrete factory
Embodied carbon emissions of cement	Nisbet et al. (2000); Hammond and Jones (2008); Indexamundi (2006); USGS (2006)
Embodied carbon emissions of aggregates	Hammond and Jones (2008)
Embodied carbon emissions of steel	World Steel Association (2008)
Carbon emissions from waterborne transportation	DEFRA (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 precast concrete factory
Emission factor of electricity generation	NEA (2009)
Emission factor of idling trucks	Stodolsky et al. (2000)
Emission factor of illumination in the precast concrete factory	Horgan (2010); ETAP (2010)

## The value chain in precast concrete production

The value chain describes the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use (Kaplinsky and Morris, 2001, p.4). In a simple value chain, there are four typical phases, which are design, production, marketing, and consumption and recycling. Precast concrete production involves many activities, including ordering raw materials, setting up the moulds, managing the stocks, etc. Examined by a “cradle-to-gate” concept, these production activities in precast concrete factories can be identified to fall into four phases, which are site layout management, delivery management of raw materials, production management, and stock management, as illustrated by Figure 1 and described below.

- **Site Layout Management:** The precast concrete factory is designed for the production activities. The site layout of the factory may affect the overall efficiency and energy consumption of the production process and this is the stage where site layout management is applied.
- **Delivery Management:** How the precasters manage the order and delivery so that it will not cause disruptions to the other production activities in the precast concrete factory may affect the sustainability factors identified above.
- **Production Management:** The actual production process by transforming raw materials into finished products, which usually includes setting up moulds, concreting, demoulding and quality check. The third value is referred to as production management in this research.
- **Stock management** represents the fourth value in the overall value chain in precast concrete production. As time and energy will be consumed when building up inventory and singling out the products for delivery, an inefficient stock management will obstruct the production process from being sustainable.



**Figure 1 A typical value chain in precast concrete production**  
(Source: Wu and Low, 2011)

The production process is usually examined under a transformation concept in modern scientific management where the overall process can be decomposed into several subprocesses. According to the transformation concept, the overall production process can be improved by improving the efficiency of the subprocesses. However, when examined by the lean production concept, this strategy does not always lead to improvement. The importance of examining the value chain of precast concrete production is that:

- Efficiency in single subprocess is only a necessary condition to the overall production efficiency. It means that even if all the subprocesses in the production process are efficient, the production can still be inefficient.
- Research into the sustainability of precast concrete production involves many dynamic factors (e.g. carbon emissions in this study) that an in-depth understanding of the dynamic factors within the whole value chain is critical.
- Achieving sustainability in precast concrete production requires a systematic integration of all the dynamic factors so that the value chain should be analyzed as a whole.

## Site layout management

The non-value adding activities identified in the questionnaire were rated by Precaster A based on two factors, which were probability of occurrence and its impact on the level of carbon emissions. Following the screening procedure, Precaster A appeared to be facing 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 these changes, the process to design and produce such precast concrete products had to be re-developed, in which case the previously manufactured products would no longer be used.

**Over provision for material storage.** The material storage area occupied 26.4% of the total area in the site layout design. The direct consequence of such large storage was unnecessary loading and unloading activities caused by singling out and transferring activities. The other source of carbon emissions generated by large storage area was the waste of either raw materials or finished products. According to the project manager interviewed, there was a 2% waste of raw materials and a 3% waste of finished products.

**The site layout is not carefully planned to achieve economic and efficient production.** Although Precaster A claimed to have an economic and efficient site layout design, the site layout was not designed to be lean. For example, the reinforcements delivered from suppliers were sent to the 2nd and 3rd floor of the factory for fabrication. When the fabrication was completed, reinforcement cages were then delivered to the storage area in the first floor before production.

**Does not think of green building materials.** Precaster A 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 really has a dramatic impact on the carbon footprint of the concrete. According to Prusinski et al. (2006), carbon emissions savings for precast concrete ranged from 137 to 222 kg/m<sup>3</sup> if slag cement mixtures were adopted. However, only regular cement (Portland cement) was adopted in current precast concrete production.

**Site layout plan is not placed on the notice board for information.** On the notice board of Precaster A, 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 lean concept, 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.

## Delivery management

Similar to the site layout management, there were a few non-value adding in the delivery management which might cause the increase in the level of carbon emissions. These non-value adding activities included:

**Large quantity supply base.** Large quantity supply base could lead to large storage area. Ballard et al. (2002) proposed a decoupling buffer between pre-manufacturing and manufacturing to reduce inventory. According to Ballard et al. (2002), the customer orders (which is the advance orders mentioned before) 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. Freight Operator Recognition Scheme in the UK).

**Transportation is 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 Precaster A. 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.

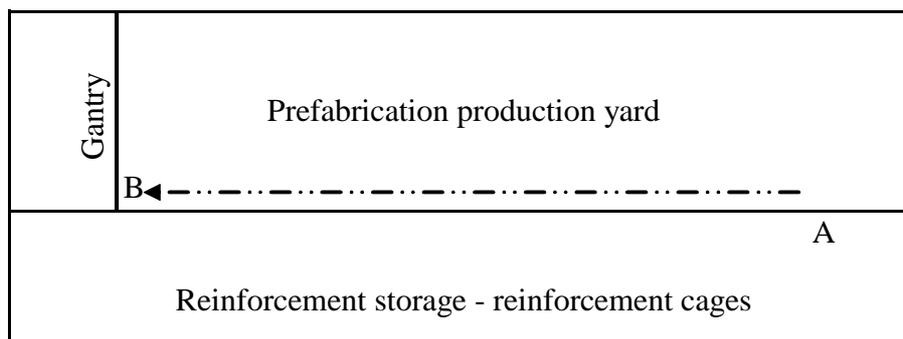
## Production management

The production process of precast concrete products involves the use of the gantry system and some other equipment. Due to the involvement of equipment, facilities managers and operators should have the greatest potential to reduce energy consumption and carbon emissions. However, there were several types of non-value adding activities that were observed in Precaster A, which include:

**Waste of raw materials and damages of raw materials.** Both factors led to the 2% waste of raw materials, as mentioned previously.

**Raw materials do not meet specifications.** According to the project manager interviewed, re-order and re-delivery of raw materials happened occasionally due to unsatisfied quality.

**Unnecessary materials handling.** When observed in Precaster A, 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 location A, he was asked to carry out the lifting process in location B, as shown in Figure 2. This unnecessary movement was caused by incompetent employees and the lack of a written production manual.



**Figure 2 A type of unnecessary movement in precast concrete production**  
(Source: Wu and Low, 2011)

**Wait time.** The two most important categories of wait time in Precaster A were wait time for inspection and labor. When the finished precast concrete products were placed on the trailer and final 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.

**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 provided. The connection between these 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 delivery do happened in Precaster A, although in an extremely low frequency about once or twice a year.

**Inadequate work crews, weak employees and lack of supervision.** Precaster A 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 in the overall value chain in precast concrete production. As time and energy will be consumed when building up inventory and singling out the products for delivery, an inefficient stock management will obstruct the production process from being sustainable. Three types of non value adding activities were observed in Precast A, which include:

**Inappropriate 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 the case in Precaster A. 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 such loading and unloading activities. Sudden accelerating and braking would cause an increase in the level of carbon emissions.

**Unclear identification marks and unclear delivery notes.** According to Precaster A, two wrong deliveries have happened due to unclear identification marks and unclear delivery notes in the contract period.

**Lack of sufficient care.** Precaster A 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.

## Results and discussions

The overall calculation of the lean improvement is shown in Table 2. The effective carbon of the precast concrete column is 609.59 kg (Wu and Low, 2011). The amount of carbon emissions caused by producing one precast concrete column can be expressed by the following formula:



The amount of CO<sub>2</sub> emissions = 609.59 + (18.29+9.29) + 9.933 + 13.11 (kg)  
 Effective carbon                      Waste                      Capital Facility

**Table 2 Carbon reduction achieved by applying the lean production philosophy**  
 (Adapted from Wu and Low, 2011)

Category	The amount of carbon emissions (kg CO <sub>2</sub> / column)
<b>Waste of finished products</b>	18.2900
- 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>	13.1100
- Over provide material storage	
- Large quantity supply base	
- Too much inventory in factory	
<b>Waste of raw materials</b>	9.2900
- 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>Inappropriate production arrangements</b>	9.9330
- Improper specification of building materials	7.2500
- Over provide material storage	0.5800
- The site layout is not carefully planned to achieve economic and efficient production	0.9600
- Transportation is not taken into consideration	0.5800
- Raw materials do not meet specifications	0.4700
- Unnecessary materials handling	0.0030
- Double-handling or delivery due to unsatisfied quality or specifications	0.0900
<b>Delivery performance</b>	0.1400
- Unclear identification marks	0.0700
- Unclear deliver notes	0.0700
<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	
- Inappropriate staffing arrangement	
- Lack of sufficient care	

Efficiency in single subprocess is only a necessary condition to the overall production efficiency. This applies to sustainability as well. When examined by the lean concept, it is found that many non-value adding activities happened in the precast concrete production process. The lean production philosophy advocates examining the refined production process where all non-value adding activities are removed in the value chain. This can usually be achieved through the VSM tools. The dynamic factors in sustainability (e.g. the carbon emissions value in this study) can therefore be investigated to achieve overall sustainability for the production process.

Research into the sustainability of precast concrete production involves many factors, including economic (e.g. production costs), social (e.g. labor issues) and environmental factors (e.g. carbon emissions, solid waste, noise, etc.). Although the contribution of the lean concept to sustainability has been identified in previous studies (e.g. Huovila and Koskela, 1998; Riley et al., 2005; Ferng and Price, 2005; Luo et al., 2005; Lapinski et al., 2006), it should be noted that the contributions were too broadly defined rather than detailedly investigated.

Huovila and Koskela (1998) identified the contribution of the lean construction principles to sustainable development. The values included minimization of resource depletion, minimization of pollution and matching business and environmental excellence (Huovila and Koskela, 1998). Luo et al. (2005) applied the lean concept to prefabrication and stated that lean could contribute to improve quality and supply chain and reduce waste. Bae and Kim (2007) found that different lean applications might have different results on the three pillar of sustainable development. For example, lean supply (the JIT system) might have influence on economic and environmental impacts rather than social impacts. In these studies, wastes, environmental burdens, and environmental deterioration were commonly used as the requirements posed by the environment.

It should be noted that the definition of the value will guide the preferred decisions and behavior of practitioners (manufacturers, contractors, developers, etc.). If the value concept is defined too broadly, the implications for these practitioners will be very minimal. As can be seen in the previous sections, even in the concept of global climate change, a single aspect in environmental sustainability, there are many issues that should be considered in the value chain of precast concrete production. The premise of this paper is that when considering the environment as values and analyzing the contribution of lean to the environment, more systematic approach including a narrowed-down definition of value is required.

The evaluation of environmental values tended to use technical, computational approaches to count value (Norton and Steinemann, 2001). Many of the models that have been used in valuing climate change were based on conventional economic cost-benefit analysis (Nordhaus, 1993, 1994, 1997; Peck and Teisberg, 1992; Manne et al., 1995). However, even the advocates of such technical, computational approaches admitted that such approaches were unable to capture large-scale, ecological values (Freeman, 1993, p.485). Conventional economic analysis gave less importance to flows that would take place in the future (Broome, 1992; Price 1993, 1996). According to Padilla (2004), the application of conventional economic analysis of environmental impact removed the analysis of future impact because of its negligible present value. However, it should be noted that if future generations have certain rights that should be respected, these rights should be included in the analysis (Padilla, 2002). Similarly, the objects being valued (e.g.

companies, production process, construction process and products) with continuous improvement plans should achieve better results than the objects without such plans. The lean concept can therefore be added to these evaluation approaches to assess environmental values by taking future flows into consideration. As can be seen in the formula, waste represents the improving potential of the production system.

In addition, the LCA methodology used to measure the environmental impacts had several drawbacks that could not be overlooked. According to Hertwich et al. (1997), LCA was the most prominent and most comprehensive approach used in assessing environmental impacts, which classified emissions into categories reflecting the environmental impacts they caused, such as acidification or ozone depletion, and aggregated the emissions in each category to an equivalency potential based on how much each emission contributed to the respective impact. However, using LCA as the assessment approach may lead to a few problems, including:

- The crucial point of assessing environmental impacts is the credibility of the environmental information (Karl and Orwat, 1999). However, a LCA is only a snapshot of a product/system at a point in time under specified assumptions (Grant and Macdonald, 2009). For example, both wastes of raw materials and damages to finished products are very common when producing precast concrete products. Whether or not the wastes and damages will be included in the calculation of the embodied carbon are subject to the analyst's own LCA assumptions.
- The comprehensiveness of the environmental impacts is currently represented by a single sign. Although a single sign can offer the customers an intuitive explanation of the products' environmental compatibility, it may suppress other information when evaluating the products' environmental quality. According to Grant and Macdonald (2009), LCA has little to say about the adaptability of the system, its limits, risks or potential, which are all necessary information to evaluate the products' environmental compatibility.
- New innovative technologies often look inefficient in the early design stage and may fare poorly in LCA terms even if they are potentially of great benefit to the environment. It seems that LCA lacks a long-term view and analysis of the products' environmental performance.

The LCA evaluation method could be improved by introducing the concept of lean in the approach. The lean concept advocates assessing the environmental impacts based on a refined production process so that future flows can be taken into consideration. This is suitable to address the problem that LCA has little to say about the potential of the systems and will help the customer to identify the improving potential of the product or process. For example, if the precast concrete column is assessed by the Singapore Green Labelling Scheme (SGLS) initiated by the Singapore Environment Council (SEC, 2011) and satisfies all the criteria as green building materials, the following descriptive text and associated promotional collaterals will be attached to the column:

Eco Friendly Building Material

SGLS User Agreement Number: xxxx

Recycled Content: xx%

Carbon Emission Value: 647.103 kg per column (609.59+18.29+9.29+9.933)



With the contribution of the lean concept, the descriptive test and associated promotional collaterals can be revised to:

Eco Friendly Building Material

SGLS User Agreement Number: xxxx

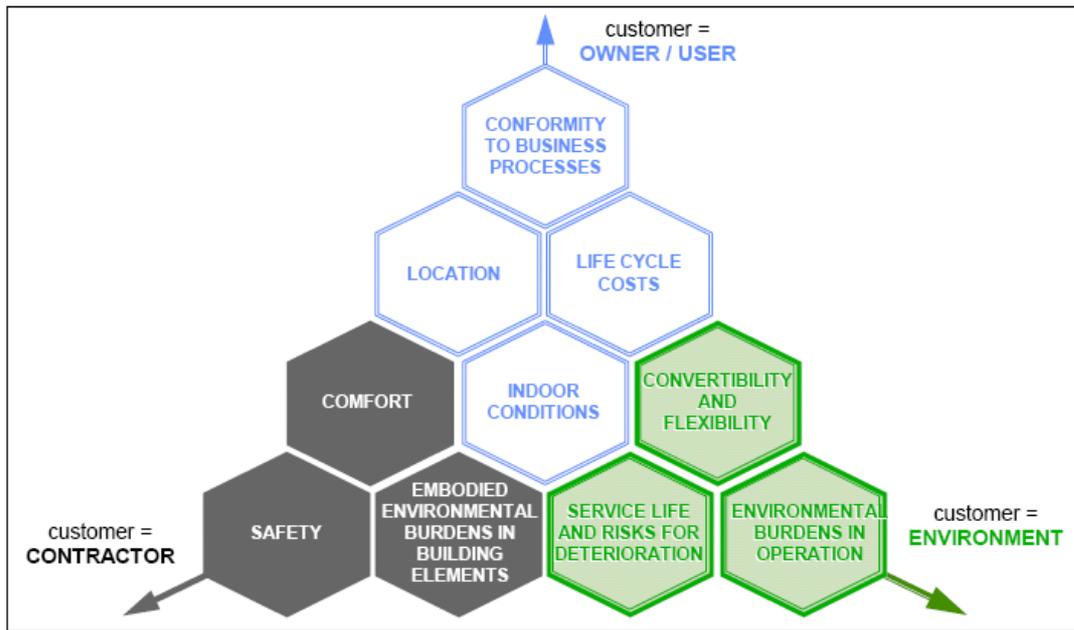
Recycled Content: xx%

Carbon Emission Value: 647.103 kg per column

Lean value: 37.513 kg per column (18.29+9.29+9.933) or 5.80% of the Carbon Emission Value

Moreover, the lean concept contributes to the interpretation of the environment as customer. Most researchers agreed that the environment should be a potential customer to the facility (e.g. Ofori, 1992; Porter and van der Linde, 1995; Huovila and Koskela, 1998). There was a trade-off from the environmental point of view, if the owner and the contractors had different economic and social priorities, which both differentiated from the environmental priorities (Huovila and Koskela, 1998). This trade-off can be seen in Figure 3. Porter and van der Linde (1995) stated that successful environmentalists and companies would reject the old trade-offs and build on the underlying economic logic that linked the environment, resource productivity, innovation and competitiveness.

Based on the lean concept, the trade-off relationship between different parties and different sustainability factors (economic, social and environmental) does not always stand. There are some areas that the product, process and facility can be improved while achieving both economic and environmental sustainability (e.g. the management of idling trucks that can be improved by apply the JIT concept; the production management that can be improved by focusing on a smooth work flow). As can be seen through the production cycle, these areas represent a large proportion of the effective carbon that can be reduced by applying the lean concept. Both economic and environmental benefits can be achieved by eliminating these non-value adding activities. In addition, one concept that cannot be overlooked here is environmental tolerance - the environment has the ability to endure unfavorable environmental impacts. Economic factors can be prioritized in production and construction activities that are conducted under the tolerance limits. Although the lean concept does not contribution directly to estimate the tolerance limits of the environment, it proposes a similar conception - to use lean to reflect how much the products/process should affect the environment. If the product/process outperforms the threshold established by the lean concept, it may be suggested that economic priorities can be focused upon.



**Figure 3 Classified requirements for a facility and their possible priorities for different customers**  
(Source: Huovila and Koskela, 1998)

## 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, inappropriate production arrangement and capital facilities can be reduced if such non-value adding activities are eliminated. For the precast concrete column examined in this study, an amount of 8.3% carbon emissions can be reduced when the lean production philosophy is adopted. 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, these 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. The lean production philosophy uses a refined production process, based on which the sustainable improvements are obtained. However, as stated previously, there are many dynamic factors in sustainability

that in-depth investigation of each dynamic factor is necessary in order to guide the precasters' decisions and behaviours.

In addition, it is found that the lean production philosophy can provide a lean benchmark for construction materials. It offers relative measurements of the sustainability factors for construction materials based on the best operations that can be achieved, which is a long-term comparison. By obtaining this level of information, contractors and developers can choose the truly environment-friendly materials and the construction industry can then move towards being a low carbon industry.

## References

- Abdulmalek, F.A. and Rajgopal, J. (2007). Analyzing the benefits of lean manufacturing and value stream mapping via simulation: a process sector case study. *Int. J. Production Economics*, 107 (1), pp. 223-236.
- Alarcón, L.F., Pavez, I., Diethelm, S. and Rojo, O. (2006). Preparing contractor organizations for implementing lean construction. In Songer, A. et al. (eds), *Proceedings of 2<sup>nd</sup> Specialty Conference on Leadership and management in Construction*, Grand Bahama Island, May 4-6, 2006.
- Alarcón, L.F. and Diethelm, Sven. (2001). "Organizing to Introduce Lean Practices in Construction Companies." *Proceedings 9th International Workshop on Lean Construction*, National University of Singapore, Singapore, August, 2001.
- Bae, J.W. and Kim, Y.W. (2007). Sustainable value on construction project and application of lean construction methods. In Pasquire, C. and Tzortzopoulos, P. (eds), *Proceedings of IGLC-15*, 16-22 July, Michigan, USA, pp.312-321.
- Ballard, G., Harper, N. and Zabelle, T. (2002). "An application of lean concepts and techniques to precast concrete fabrication". In *Proceedings of IGLC-10*, Gramado, Brazil.
- Blumenthal, A. (2008). Lean logistics, lessons learnt from Japan. [online] Available from: [http://www.leanconstruction.org.uk/lci\\_uk\\_summit\\_2008](http://www.leanconstruction.org.uk/lci_uk_summit_2008) (accessed 9th Aug 2010)
- Broome, J. (1992). *Counting the costs of global warming*. Cambridge: White Horse Press.
- Callicott, J.B., 1984. Non-anthropocentric value theory and environmental ethics. *American Philosophical Quarterly*, 21, pp.299-309.
- Callicott, J.B., 1986. On the intrinsic value of nonhuman species. In B.G. Norton, ed. *The preservation of species*. Princeton, NJ: Princeton University. pp.138-72.
- Callicott, J.B., 1995. environmental ethics: overview. In W.T. Reich, ed. *The preservation of species*. Princeton, NJ: Princeton University. pp.138-72.
- DEFRA. (2005). Guidelines for Company Reporting of Greenhouse Gas Emissions. London. [online] Available from: <http://www.defra.gov.uk/environment/business/reporting/pdf/envrpgas-annexes.pdf> (accessed 9th Oct 2010)
- EPA. (2003). *Lean Manufacturing and Environment*. [Online] Available at: <http://www.epa.gov/lean/performance/index.htm> [Accessed 14 Nov 2010].
- ETAP. (2010). Excellent Lighting, Saving Energy. [online] Available from: [http://www.etaplighting.com/uploadedFiles/Downloadable\\_documentation/documentatie/Excellent%20lighting%20saving%20energy%20-%20Engels\(1\).pdf](http://www.etaplighting.com/uploadedFiles/Downloadable_documentation/documentatie/Excellent%20lighting%20saving%20energy%20-%20Engels(1).pdf) (accessed 20th Aug 2010)
- Evanson, D. (2008). Lean construction logistics requirements within London, The LCI-UK Summit 2008. Available from: [http://www.leanconstruction.org.uk/lci\\_uk\\_summit\\_2008](http://www.leanconstruction.org.uk/lci_uk_summit_2008) (accessed 20th Aug 2010)



- Ferng, J. and Price, A.D.F. (2005). An exploration of the synergies between Six Sigma, total quality management, Lean construction and sustainable construction. *Int. J. Six Sigma and Competitive Advantage*, Vol. 1, No. 2, pp. 167-187.
- Freeman, R. (1993). *The measurement of environmental and resource values*. Washington, D.C.: Resources for the Future.
- Grant, T. and Macdonald, F. (2009). Life cycle assessment as decision support: a systemic critique. In R. Horne, K. Verghese & T. Grant, eds. *Life cycle assessment: principles, practice and prospects*. Collingwood: CSIRO Publishing.
- Hammond, G. and Jones, C. (2008). Inventory of Carbon and Energy (ICE). [online] Available from: <http://www.bath.ac.uk/mech-eng/sert/embodied/> (accessed 16th Mar 2010)
- Herrmann, C., Thiede, S., Stehr, J., Bergamnn, L. (2008). An environmental perspective on Lean Production, in proceedings of the 41<sup>st</sup> CIRP Conference on Manufacturing Systems, 2008. Tokyo, Japan, Springer, Berlin, pp. 83-88.
- Hertwich, E.G., Pease, W.S. and Koshland, C.P. (1997). Evaluating the environmental impact of products and production processes: a comparison of six methods. *Science of the Total Environment*, 196(1), pp.13-29.
- Horgan, E. (2010). Lighting carbon reduction. [online] Available from: <http://www.uel.ac.uk/greenthing/documents/AssociationofUniversityEngineers-LIGHTING24052010.pdf> (accessed 20th Aug 2010)
- Howell, G.A. (1999). "What is Lean Construction". Proc. 7th Ann. Conf. Intl. Group for Lean Constr. IGLC-7 26-28 July, held at U.C. Berkeley, CA.
- Howell, G. and Ballard, G. (1998). "Implementing lean construction: understanding and action". 6<sup>th</sup> Ann. Conf. Intl. Group for Lean Constr. IGLC-6 13-15 August, held at Guarujá, Brazil.
- Huovila, P. and Koskela, L. (1998). Contribution of the Principles of Lean Construction to Meet the Challenges of Sustainable Development. In Formoso, C.T. (ed.), Proceedings IGLC-6, 13-15 August, held at Guarujá, Brazil.
- Indexmundi. (2006). Cement: World Production, By Country. [online]. Available from: [http://www.indexmundi.com/en/commodities/minerals/cement/cement\\_t22.html](http://www.indexmundi.com/en/commodities/minerals/cement/cement_t22.html) (accessed 14th Jan 2010)
- Kaplan, R. and Norton, D. (1996). *The balanced scorecard*. Boston: Harvard Business School Press.
- Kaplinsky, R. and Morris, M. (2001). "A Handbook for Value Chain Research". <<http://www.globalvaluechains.org/docs/VchNov01.pdf> > (Aug 18, 2009)
- Karl, H. and Orwat, C. (1999). Economic aspects of environmental labelling. In H. Folmer & T. Tietenberg, eds. *The international yearbook of environmental and resource economics 1999/2000: a survey of current issues*. Cheltenham: Elgar. pp.107-33.
- Klotz, I., Horman, M. and Bodenschatz, M. (2007). A lean modelling protocol for evaluating green project delivery. *Lean Construction Journal*, Vol.3, No.1, pp.1-18.
- Koskela, L. (1992). "Application of the new production philosophy to construction". CIFE technical report#72, Stanford University.
- Lapinski, A.R., Horman, M.J. and Riley, D.R. (2006). Lean processes for sustainable project delivery. *Journal of Construction Engineering and Management* 132 (10), pp. 1083-1091.
- Low, S.P., Liu, J.Y. and Wu, P. (2009). Sustainable facilities: institutional compliance and the Sino-Singapore Tianjin Eco-city Project. *Facilities* 27 (9/10), pp.368-386.
- Luo, Y., Riley, D., and Horman, M.J. (2005). Lean Principles for Prefabrication in Green Design-Build (GDB) Projects. In Russell, K. (ed.), Proceedings of IGLC-13, 18-21 July, Sydney, Australia.

- Manne, A., Mendelsohn, R. and Richels, R. (1995). MERGE: a model for evaluating regional and global effects of GHG reduction policies. *Energy Policy*, 23(1), pp.17-34.
- McKinnon, A. (2008). CO<sub>2</sub> Emissions from Freight Transport in the UK. Logistics Research Centre.
- Nahmens, I. (2009). From Lean to Green Construction: A Natural Extension. Conference Proceeding Paper Building a Sustainable Future. Proceedings of the 2009 Construction Research Congress, pp. 1058-1067.
- Nash, R.F., (1989). *The rights of nature*. Madison: University of Wisconsin.
- NEA (National Environment Agency). (2009). Information on emission factors. [online] Available from: <http://www.nccc.gov.sg/cdm> (accessed 19th Jan 2009)
- Nisbet, M., VanGeem, M.g., Gajda, J. and Marceau, M. (2000). Environmental Life Cycle Inventory of Portland Cement Concrete. SN. 2137. Portland Cement Association: Skokie.
- Nordhaus, W.D. (1993). Rolling the dice: an optimal transition path for controlling greenhouse gases. *Resource and Energy Economics*, 15(1), pp.27-50.
- Nordhaus, W.D. (1994). *Managing the global commons: the economics of climate change*. Cambridge MA: MIT Press.
- Nordhaus, W.D. (1997). Discounting in economics and climate change. *Climate Change*, 37(2), pp.315-28.
- Norton, B. (1991). Thoreau's insect analogies: or, why environmentalists hate mainstream economists. *Environmental Ethics*, 13(3), pp.235-51.
- Norton, B.G. and Steinemann, A.C. (2001). Environmental values and adaptive management. *Environmental Values*, 10(4), pp.473-506.
- Ofori, G. (1992). The environment: the fourth construction project objective? *Construction Management and Economics*, 10(5), pp.369-95.
- Padilla, E. (2002). Intergenerational equity and sustainability. *Ecological Economics*, 41(1), pp.69-83.
- Padilla, E. (2004). Climate change, economic analysis and sustainable development. *Environmental Values*, 13(4), pp.523-44.
- Peck, S.C. and Tiesberg, T.J. (1992). CETA: a model for carbon emissions trajectory assessment. *Energy Journal*, 13(1), pp.55-77.
- Peyroteo, A., Silva, M. and Jalali, S. (2007). Life Cycle Assessment of Steel and Reinforced Concrete Structures: A New Analysis Tool. Portugal SB 2007. Sustainable Construction, Material and Practices, IOS Press: 397-402.
- Phillipson, M. (2003). "Defining the Sustainability of Prefabrication and Modular Process in Construction". DTI Construction Industry Directorate Project Report, Building Research Establishment, Garston.
- Porter, M.E. (1985). *Competitive advantage: creating and sustaining superior performance*. New York: Free Press.
- Porter, M.E. and van der Linde, C. (1995). Green and competitive: ending the stalemate. *Harvard Business Review*, September-October.
- Price, C. (1993). *Time, discounting and value*. Oxford: Blackwell.
- Price, C. (1996). Discounting and project appraisal from the bizarre to the ridiculous. In C. Kirkpatrick & J. Weiss, eds. *Cost-Benefit Analysis and Project Appraisal in Developing Countries*. Cheltenham: Edward Elgar.
- Prusinski, J.R., Marceau, M.L. and VanGeem, M.G. (2006). Life cycle inventory of slag cement concrete. In Naik, T. (ed.), Proceedings of the Eighth International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete-CANMET/ACI. Pp.65-91.
- Riley, D., Sanvido, V., Horman, M.J., McLaughlin, M., and Kerr, D. (2005). Lean and Green: The Role of Design-Build Mechanical Competencies in the Design and Construction of

- Green Buildings. In Tommelein, T. (ed.), Proceedings of the 2005 Construction Research Congress, April 5-7, San Diego, CA
- Rolston, H. (1988). *Environmental ethics*. Philadelphia: Temple University.
- Rother, M. and Shook, J. (1999). "*Learning to see: value stream mapping to create value and eliminate muda*". The Lean Enterprise Inst., Brookline, Mass.
- Satterfield, T. (2001). In search of value literacy: suggestions for the elicitation of environmental values. *Environmental Ethics*, 10(3), pp.331-59.
- SEC. (2011). Singapore Green Labelling Scheme. Available from: <http://www.sec.org.sg/awards/greenlabel/criterion> (accessed 21st Mar 2011)
- Shook, J. (2003) "Helpful Hints on Mapping off the plant floor in Support or Administrative Operations". Available from: <http://www.lean.org/common/display/?o=913>. (accessed 5<sup>th</sup> Apr 2010)
- Stodolsky, F., Gaines, L. and Vyas, A. (2000) Analysis of Technology Options to Reduce the Fuel Consumption of Idling Trucks. Centre for Transportation Research, Argonne National Laboratory, Paper No. ANL/ESD - 43, 2000.
- Tommelein, I.D. and Ballard, G. (1999). "Just-In-Time Concrete Delivery mapping alternatives for vertical supply chain integration". In *Proceedings of IGLC-7*, University of California, Berkeley, CA. 97-108.
- U.S. Department of Energy. (2010). National Idling Reduction Network News, July 2010. [online] Available from: [www1.eere.energy.gov](http://www1.eere.energy.gov) (accessed 9th Aug 2010)
- U.S. Environmental Protection Agency. (2003). Lean Manufacturing and Environment. <<http://www.epa.gov/lean/performance/index.htm>> (accessed 14th Nov 2010)
- U.S. Geological Survey (USGS). (2006). Minerals Yearbook 2006. [online] Available from: <http://minerals.usgs.gov/minerals/pubs/commodity/> (accessed 15th Jan 2010)
- WCED. (1987). "Our common Future". Oxford University Press: Oxford. ^Brudtland report^ p.43.
- Wills, B. (2009) The Business Case for Environmental Sustainability (Green): Achieving rapid returns from the practical integration of Lean & Green. [online] Available from: <http://www.leanandgreensummit.com/LGBC.pdf> (accessed 9th Oct 2010)
- Winch, G.M. (2002). *Managing construction projects: an information processing approach*. Oxford: Blackwell Science.
- Wu, P. and Low, S.P. (2011). Managing the embodied carbon of precast concrete columns. *ASCE Journal of Materials in Civil Engineering* (accepted for publication)
- Womack, J.P. and Jones, D.T. (1996). "Lean Thinking". Simon & Schuster, New York
- World Steel Association (WSA). (2008). Sustainability Report of the World Steel Industry. [online] <http://www.worldsteel.org/?action=publicationdetail&id=52> (accessed 14th Jan 2010).
- Yates, J.K. (2007). "Global Engineering and Construction". John Wiley & Sons, Inc., Hoboken, New Jersey.