RESEARCH

USING LEAN PRACTICES TO IMPROVE CURRENT CARBON LABELLING SCHEMES FOR CONSTRUCTION MATERIALS—A GENERAL FRAMEWORK

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ABSTRACT

The construction industry has considerable environmental impacts through the process of manufacturing building materials and building construction. Many environmental labelling programs have been introduced to the construction industry to measure the environmental impacts, including building up the environmental profiles for building materials. Although absolute measurements of the environmental impacts can be obtained by these labelling programs through detailed Life Cycle Assessment (LCA) studies, relative measurements should not be overlooked to indicate the gap between the current and the "leanest" performance. The term "lean" is often used to describe a process with less wastes, materials, human effort, time, etc. The lean concept originates from the Toyota Production System and has been applied in the automobile industry for decades. This paper therefore aims to investigate the applicability of a relative measurement of the environmental impacts for building materials by introducing the concept of "lean score". The research aim is narrowed down by choosing the carbon labelling program and the precast concrete products as research objectives. The results indicate that a "lean" benchmark can be built to offer relative measurements of carbon emissions for precast concrete products. The lean score obtained from the benchmarking process provides the improving potential that can help the construction industry move towards sustainability. The results are also useful for regulatory bodies to establish national standards to measure the environmental impacts for building materials.

KEYWORDS

carbon emissions, climate change, sustainable development, prefabrication, lean production

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INTRODUCTION

With the rising recognition of sustainable development, environmental labelling programs are designed to evaluate environmental impacts, especially in the construction industry, which has been recognized as the biggest consumer of natural resources and energy. In the United States, buildings account for: 1) 36% of total energy use and 65% of electricity consumption; 2) 30% of greenhouse gas emissions; 3) 30% of raw materials use; 4) 30% of waste output, which is 136 million tons annually; and 5) 12% of potable water consumption (U.S. Green Building Council, 2004). In the United Kingdom, it was recorded that: 1) 10% of the carbon emissions arise from the production and use of building materials; 2) the construction industry uses 6 tons of building materials per head of population every year; and 3) materials production and construction accounts for an estimated 122 million tons of waste, or 30% of the total waste (Vijayan and Kumar, 2005). The enormous consumption of natural resources imposes detrimental burden on the environment. These detrimental burdens are normally recognized as environmental impacts, which include global climate change, ozone depletion, water extraction, acid deposition and mineral extraction.

Of all the environmental impacts, global climate change is receiving increasing acknowledgement as a significant issue that causes a considerable threat to human development. According to the Intergovernmental Panel on Climate Change (2007), eleven of the last twelve years (1995–2006) ranked among the twelve warmest years in the instrumental record of global surface temperature since 1850. Billions of people are exposed to natural disasters caused by this ever-changing climate, which take lives, damage infrastructures and resources, disrupt economic activities and threaten social development (Pelling, et al., 2004). If actions are not taken to reduce greenhouse gas emissions, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP per year, on an ongoing basis (Stern, 2007).

As the largest source of carbon emissions, the construction industry may face increasing pressure to achieve sustainability, including developing many environmental labelling programs (American Institute of Architects, 2007) According to Hemmelskamp and Brockmann (1997), environmental labels that serve as quality marks for products according to selected criteria can be used to verify their environmental compatibility. While an overall assessment for all the environmental impacts may be difficult, many environmental labelling programs focus on a single criterion, such as carbon emissions (i.e. the carbon labelling programs) and energy consumption (e.g. the Energy Star Program in the U.S.). According to Ball (2002), most labelling programs follow the Life Cycle Assessment (LCA) rules and can offer an absolute measurement of the single criterion that is chosen for the assessment. For example, the carbon labelling program focuses on the inputs of materials and energy to estimate the carbon level of the finished products. The impacts of different products on global climate change can therefore be assessed through the comparison of their carbon levels.

The lean concept has been used in the construction industry for decades to reduce waste and increase efficiency. The core of the lean concept is the observation that there are two aspects in all production systems: conversions and flows (Koskela, 1992). Conversions activities refer to those which add value to the product/process, while flow activities refer to those non-value adding activities. Benchmark is one of the most principles in lean construction to achieve continuous improvement (Gurumurthy and Kodali, 2009). The lean concept suggests that it is possible to make a relative comparison between the current practice and the best practice (which is referred to as lean benchmark in this study). However, it appears that so far no studies have been conducted to investigate the relative comparison in environmental labeling programs.

In this context, the precast concrete products are chosen for illustration purposes in this study. Precast concrete products are widely adopted in the construction industry to achieve speedy construction when carrying out "system building" types of construction projects. Due to its benefits towards fire resistance, thermal performance, sound insulation and durability, it has been widely adopted in housing projects in UK, Japan, USA and other countries (Glass, 2000). According to Glass (2000), precast concrete represents about 25% of the market for cementitious products, including a wide range of products such as blocks, pavings, suspended floors, hollow cores, cast stone and architectural claddings and there is a market potential in EU countries to adopt precast concrete products. As observed in precast concrete factories, many non-value adding activities happened frequently in the production process and might adversely affect the labelling score of the products (Wu and Low, 2011). Low and Mok (1999) found that the prefabrication yard can be improved to raise productivity. Ballard et al. (2003) found that substantial improvements in work flow can be achieved with little capital investment and without changing technology or how specific operations were performed. This study therefore aims to: 1) investigate the contribution of the lean concept to improve current carbon labelling programs by offering a relative comparison; and 2) develop a general framework to apply the lean concept in carbon labelling programs.

ENVIRONMENTAL LABELLING PROGRAMS AND CARBON LABELLING SCHEMES

Driven by the pressing pressure of environmental challenges, there have been a number of attempts to initiate environmental labelling or eco-labelling schemes (Ball, 2002). Environmental labelling programs may provide one or several pieces of environment-related information, such as modelling of energy consumption, water consumption, carbon emissions and wastes. These pieces of information are aggregated into a single score for making decisions when selecting materials. In the building and construction industry, the labelling programs can be used to assess the whole building performance as well as the performance of construction materials. Trusty (2001) divided the labelling programs into three levels, which are:

- Level 1: Product comparison tools (e.g. UK Ecopoints, Blue Angel, NF Environment Mark)
- Level 2: Whole building design or decision support tools (e.g. Whole Life Cycle Costing, Multi-Criteria Decision Making)
- Level 3: Whole building assessment frameworks (BREEAM, LEED®, Green Globes)

For example, LEED® (the Leadership in Energy and Environmental Design) is a voluntary consensus standard developed by the U.S. Green Building Council (USGBC) for developing sustainable buildings that have superior performance in the areas of sustainable site development, water savings, energy efficiency, materials selection and indoor air environmental quality (Vijayan and Kumar, 2005). Green Globes offer a simpler methodology and employ a user-friendly interactive guide for assessing and integrating green design principles for buildings (Smith, et al., 2006). Both labelling programs are known as the whole building performance assessment tools. On the other hand, *the BRE methodology for environmental profiles for construction materials, components and buildings* offers a standardized method to identify and assess the environmental effects associated with building materials over their life cycle—that is the extraction, processing, use, maintenance and eventual disposal (Building Research Establishment, 2010). Based on the methodology, the UK Ecopoints was initiated by BRE to measure the total environmental impacts of a particular product or process (Huovila and Curwell, 2007). Environmental labelling programs of construction materials should be completed in close cooperation with manufacturers, as information related to inputs of raw materials, energy as well as the detailed design is mostly provided by manufacturers. The Whole Life Cycle Costing approach is a technique which enables comparative cost assessments to be made over specified period of time, taking into account all relevant economic factors both in terms of initial costs and future operational costs (Gluch and Baumann, 2004). According to Balcomb and Curtner (2000), the Multi-Criteria Decision-Making (MCDM) technique is designed to guide design teams in a way that makes sustainable building design easy and inexpensive. Both approaches belong to the Level 2 assessment (i.e. whole building design or decision support tool) and can offer the design team a good evaluation of the proposed building to achieve ultimate building sustainability. In accordance with the research aim, this study focuses on the review of environmental labelling methods for construction materials (i.e. Level 1 assessment) instead of the whole building assessment and the decision support tools.

Carbon labelling schemes of building materials are designed to address the impact of global climate change to the construction industry. 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 important factors. The design of carbon labelling programs often follows the LCA rules, similar to other environmental labelling programs, by assigning elementary flows and potential environmental impacts to a specific product system. The whole labelling process consists of estimating the inputs of raw materials, energy, the emissions to air, land and water associated with the manufacture of a product, operation of a process or provision of a service (Nisbet et al., 2000). While a LCA study usually involves several kinds of environmental impacts, only the impact of carbon emissions is considered in a carbon labelling program.

There are few carbon labelling schemes for construction materials. Most carbon labelling schemes were integrated in the environmental labelling programs. As shown in Table 1, the most commonly adopted strategy to calculate the carbon emissions values is to use LCA techniques. This strategy is also adopted in current environmental labelling programs, which are designed and tested under life cycle assessment (LCA)—a method to evaluate the environmental impacts in the life cycle of the products (ISO 14040-14043).

TABLE 1. Carbon labelling practices in current environmental labelling programs.

Environmental labelling programs	Carbon labelling practices under the program
EU – Ecolabel	Assess the GHG emissions of the products based on key LCA techniques and principles
UK – The Ecopoints	Use LCA techniques to transfer to GHG emissions into ecopoints – 1 kg of CO_2 equivalent gets 0.0029 ecopoints
Singapore – Singapore green labelling schemes	Use LCA techniques to address the carbon emissions values at the product's point of production (e.g. kg CO_2/ton or kg CO_2/m^3)
US – BEE® 4.0	Use LCA techniques to transfer the GHG emissions into an environmental performance score

TABLE 2. PAS 2050 principles when assessing a product's GHG emissions.

PAS 2050 Principles	Descriptions
Relevance	GHG emissions and removals data and methods appropriate to the assessment of the GHG emissions arising from specific products have been selected
Completeness	All product life cycle GHG emissions and removal arising within the system and temporal boundaries for a specified product which provide a material contribution to the assessment of GHG emissions arising from that product have been included
Consistency	Assumptions, methods and data have been applied in the same way throughout the quantification and support reproducible, comparable outcomes
Accuracy	Bias and uncertainty have been reduced as far as practical
Transparency	Where the results of life cycle GHG emissions assessment carried out in accordance with this PAS are to be disclosed to a third party, GHG emissions-related information is made available that is sufficient to support disclosure and allow such a third party to make associated decisions with confidence

(Adapted from: British Standards Institution, 2011)

PAS 2050 was published by the BSI on 29 October 2008 and included details requirements for the assessment of GHG emissions arising from goods and services (Sinden, 2009). The newly revised PAS 2050:2011 clearly stated that assessment of the GHG emissions of products shall be carried out using LCA techniques (British Standards Institution, 2011). The new ISO 14067 *Carbon footprint of products—requirements and guidelines for quantification and communication* is still under development at the time of this study. However, it can be reasonably assumed that the standard will follow the LCA techniques, similar to PAS 2050. According to ISO 14040 (2006), LCA can be used in product development and improvement, strategic planning, environmental performance indicator selection and marketing. It can be used to classify emissions into groups categorized by the environmental impacts they may cause and aggregate the emissions in each category to an equivalency potential based on how much each emission contributes to the respective impact. In PAS 2050, there are five principles that should be followed when assessing a product's life cycle GHG emissions. These principles are shown in Table 2.

However, environmental labelling programs which use LCA as the assessing approach may lead to a few problems, including:

1. The crucial point of environmental labelling is the credibility of the ecolabel 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, wastes of raw materials and damages to finished products are very common when producing precast concrete products. Whether or not the wastes and damages are included in the calculation are subject to the analyst's own LCA assumptions. This may affect the completeness principle, which clearly stated that all product life cycle GHG emissions arising within the system and temporal boundaries for a specified product should be included for assessment. When this principle is violated, the consistency principle will not stand because it is therefore difficult to provide comparable outcomes between different products based on incomplete results.

2. The comprehensiveness of the ecolabel information 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. The single sign will affect the transparency principle because it is unrealistic for third parties (e.g. customers) to make associated decisions (e.g. to purchase the product or not) based on a single sign, especially when the GHG values of the products are close. Doublet and Jungbluth (2010) stated that a comprehensive list of environmental product information (EPI) should be provided along with the product to make transparent and comparable communication. Bare et al. (1999) argued that although there are benefits to use the endpoints of the products (i.e. the true life cycle) in LCA studies, the comprehensiveness of the assessment is narrowed down because many more assumptions and value judgements have to be made.
3. New innovative technologies often look inefficient in the early design stage and can fare poorly in LCA terms even if they are potentially of great benefit to the environment. In addition, products that involve a continuous improvement plan should have better performance in the LCA than the products without such plans. However, the continuous improvement section is currently overlooked in most LCA assessments. It seems that LCA lacks a long-term view and analysis of the products' environmental performance.

According to Cole (1998), although interest in environmental assessment programs continues to increase, it is difficult to fully anticipate their future role or the way they will ultimately evolve as an integral part of the building process. Carbon labelling programs using LCA as assessment methods should continuously evolve to provide credible and comprehensive information of the products.

LEAN AND GREEN

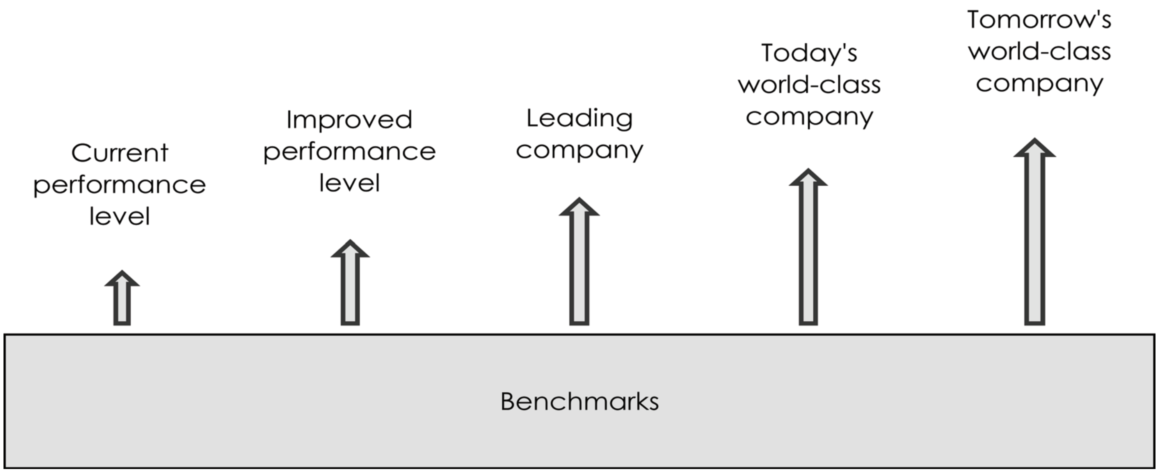
Originated from the Toyota Production System, the lean production philosophy was developed as a new way of thinking which advocated reducing or eliminating non-value adding activities as well as improving the efficiency of value adding ones at the same time. The lean philosophy can be considered as a 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:

1. Specify value by product. According to Howell and Ballard (1998), specifying value by product shapes all actions around customer requirements.
2. Identify the value stream. A value stream mapping (VSM) process can be adopted to help project managers to identify the hidden issues that may hinder the flow of activities.

3. Make production flow. Making production flow means that the production process should not be interrupted. The products that have been produced in factories should be in constant motion without stopping (Womack and Jones, 1996).
4. At the pull of the customer. The term "customer" used in this tenet can be extended to a wider background. Each work station can be identified as a "customer" and its requirement can flow back to previous work stations to regulate the activities.
5. Pursuing perfection, custom product, zero time delivery and nothing in stores.

Unlike traditional production planning tools, the lean philosophy focuses on a "systems" view of the production process, which is a higher level examination to investigate the process from beginning to end. The lean concept has proven to be effective in increasing environmental benefits by eliminating waste, preventing pollution and maximizing the owners' value (Ferng and Price, 2005). 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). U.S. Environmental Protection Agency (2003) found that lean produced 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 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 pillars of sustainable development (i.e. economic, social and environmental sustainability). For example, lean supply might have influence on economic and environmental impacts rather than social impacts. 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). Wills (2009, p.1) stated that by defining the lean concept as "the elimination of waste while adding value for customers", the lean concept and green are brought together. By applying the lean concept to the environmental labelling program, a lean benchmark using less materials and energy consumption can be provided. According to Cross and Iqbal (1995, p.4), benchmarking is: "a continuous systematic process to evaluate companies recognized as industry leaders, to determine business and work processes that represent best practices and to establish rational performance goals". Kreuz (1997, p.82) quoted benchmarking as "an objective, comparative evaluation of organizational structures, costs, technologies, performance indices and processes through indicators generated in the direct analysis of data and information of a representative group of similar or competitive companies classified as world-class companies". In fact, Koskela (1992) stated that one of the most important principles of the lean concept is benchmarking, i.e. to compare the world leader for continuous improvement. Benchmarking involves both short term and long term scopes. As shown in Figure 1, a short term scope should include competitors and leading companies in the industry while a long term scope usually use today's and tomorrow's world-class companies as benchmarks. Lean benchmark involves both the concept of lean and benchmark. It means to compare organizational structures, costs, technologies, performance indices and processes with an entity which uses less resource, effort and time. Different from normal benchmarks which are underpinned by industry or world class leaders, a lean benchmark may be real or

FIGURE 1. Short term and long term benchmarks. (Sources: Kreuz, 1997, p.83)



virtual. If there are real competitors or leaders who perform "leaner" examined by the lean thinking, these competitors or leaders can be set as lean benchmarks. On the other hand, if the company is competing with the best scenario that the company may achieve, the lean benchmark is virtual.

RESEARCH METHODOLOGY

The aim of the study is to examine how the lean practices can be used to improve the carbon labelling schemes for building materials. Based on the research aim, the use of case study was considered to be appropriate. This case study used a specific type of precast concrete column in the Singapore construction industry to explain how the lean practices can be integrated into the carbon labelling programs for construction materials. The unit of analysis of this case study is a type of precast concrete column produced in Precaster A, which was step up in 1994 to spearhead the adoption of prefabrication technology in Singapore. Precaster A occupied large market share of the precast concrete market in Singapore, especially in public housing projects. The production arrangements in Precaster A would therefore reflect the general production practices in the Singapore precast concrete industry.

A four-day site investigation was conducted in Precaster A to focus on the production process for a specific type of precast concrete column, which was chosen for the LCA study. The case study was conducted in two phases: (1) the embodied carbon of the precast concrete column was firstly calculated based on the production procedure provided by the project manager using LCA techniques; (2) wastes, damages and energy consumption caused by the non-value adding activities were then recorded to create the lean benchmark. In order to calculate the embodied carbon of the precast concrete column, a process tree was obtained. Carbon emissions generated in every production process were recorded to calculate the embodied carbon. Following the process tree, the non-value adding activities were identified through the lean principles. Carbon emissions caused by these non-value adding activities were then recorded to generate the lean benchmark. Data collection methods used in the four-day site investigation included:

1. *Documentation.* Documentation information relating to the production procedure, quality control procedure and waste records were referred to in the case study.
2. *Interview.* Interviews with the project manager of Precaster A were organized to obtain the quantities of materials and energy consumption required for the LCA study.
3. *Direct observations.* Direct observations were also conducted. Information related to waste of raw materials, waste of finished products and energy consumption caused by the non-value adding activities were recorded by direct observations.

The *2006 IPCC Guidelines for National Greenhouse Gas Inventories* was referred to when calculating carbon emissions from different sources (Intergovernmental Panel on Climate Change, 2008). For example, when calculating the GHG emissions from construction wastes, the following equation can be used:

$$\text{Emissions}_{\text{materials, products}} = \text{Embodied carbon} * \text{Quantity}$$

Where:

$\text{Emissions}_{\text{materials, products}}$ = Carbon emissions by type of materials/products (kg CO_2)

Embodied carbon = Embodied emission factors by type of materials/products (kg CO_2/kg)

Quantity = amount of the materials/products consumed (kg)

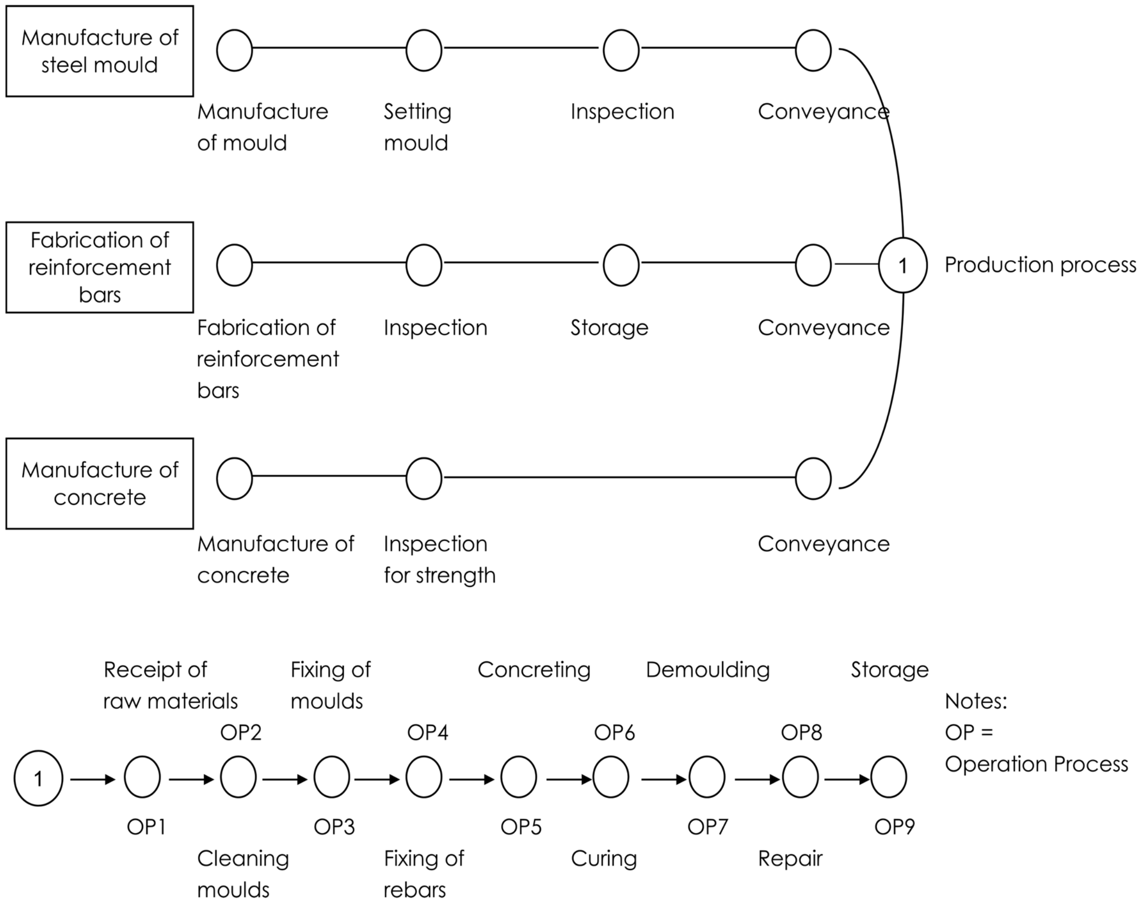
ANALYSIS

Specify value and identify the value stream

In order to calculate the embodied carbon, a process tree of the product should be defined at the very beginning. The process tree can be obtained by conducting a Value Stream Mapping (VSM) procedure, i.e. to draw a visual representation of every process in the material and information flow (Rother and Shook, 1999). Abdulmalek and Rajgopal (2007) proposed three steps in VSM to identify the types of waste in the value stream, which are: 1) to choose a particular product as the target for improvement; 2) to draw a current state map that is essentially a snapshot capturing how things are currently being done; and 3) to identify the waste in each value stage. Following the VSM procedure, a typical production process of the precast concrete column is shown in Figure 2. As illustrated in Figure 2, boxes indicate the inputs of raw materials in the overall life cycle of precast concrete products. Circles represent the potential inputs of energy in the overall life cycle of precast concrete products. The carbon labelling program should therefore consider both inputs of boxes and circles in order to calculate the carbon score.

Based on the process tree, the carbon emissions value of this product is shown in Table 3. The embodied carbon of the precast concrete column was estimated to be 647.10 kg CO_2 in the life cycle (cradle to gate) (Wu and Low, 2011). This life cycle included the extraction of raw materials, the transportation of raw materials (both international and local) and the production processes in both concrete plant and precast concrete factory. As shown in Table 3, there were three sources (points 8, 9 and 10) which did not add value to the precast concrete column from a lean perspective, including waste of raw materials, waste of finished products and inappropriate production arrangements.

FIGURE 2. The production process of the precast concrete column. (Source: Wu and Low, 2011)



Identify the interruptions through the lean principles

When examined by the lean principles, which are to make the production flow, at the pull of the customer and pursuing perfection, not all processes listed in the process tree in Figure 2 are value adding to the overall production. For example, in the lean thinking, storage is usually defined as a type of non-value adding activity, because the particular materials or products have to be singled out from the huge stockpiles. The singling out process is also defined as non-value adding activity. During the transferring and singling out process, the precast concrete products may be damaged by using handling equipment, such as fork-lifts and dumpers. In addition, it is acknowledged by many precasters that there are usually 3% to 5% waste of raw materials in the production process (Wu and Low, 2011). Damages to the finished products are also very common in precast concrete production. Waste of raw materials and damages to finished products are usually not considered in the labelling program for precast concrete products, because the inputs of LCA data, such as raw materials and energy, are usually calculated from design specifications provided by the manufacturers.

Research has been conducted to find out the non-value adding activities in precast concrete production. Ohno (1988) identified seven categories of waste: overproduction, correction, material movement, processing, inventory, waiting and motion, all of which can

TABLE 3. Carbon emissions value of the precast concrete column.

Raw materials			Emission factors		Carbon emissions		
1. Cement	320.1300	kg	0.4970	kg CO_2/kg	159.1046	kg CO_2	24.59%
2. Aggregates	540.6600	kg	0.0050	kg CO_2/kg	2.7033	kg CO_2	0.42%
3. Reinforcement	178.0000	kg	1.7000	kg CO_2/kg	302.6000	kg CO_2	46.76%
Energy inputs							
4a. Transportation (cement) (international)	320.1300	kg	104.2000	kg CO_2/ton	33.3575	kg CO_2	5.15%
4b. Transportation (aggregate) (international)	540.6600	kg	121.6000	kg CO_2/ton	65.7443	kg CO_2	10.16%
4c. Transportation (reinforcement) (international)	178.0000	kg	35.7000	kg CO_2/ton	6.3546	kg CO_2	0.98%
5. Concrete plant operation	68.6000	kWh/m^3	0.5233	kg CO_2/kWh	25.5200	kg CO_2	3.94%
6a. Transportation (concrete) (local)	24.1500	km	0.1200	kg CO_2/km /ton	9.7721	kg CO_2	1.51%
6b. Transportation (reinforcement) (local)	24.1500	km	0.1200	kg CO_2/km/ton	1.0317	kg CO_2	0.16%
7. Precast concrete production	6.5000	kWh	0.5233	kg CO_2/kWh	3.4015	kg CO_2	0.53%
				Total	609.5895	kg CO_2	94.20%
8. Waste of raw materials – 2%					9.2900	kg CO_2	1.44%
9. Waste of finished products – 3%					18.2900	kg CO_2	2.83%
10. Inappropriate production arrangements					9.9330	kg CO_2	1.53%
				Total	647.1025	kg CO_2	100%

(Adapted from: Wu and Low, 2011)

be found in the precast concrete production process. Low and Mok (1999) discovered that there are several types of waste during the manufacturing process, including waste from over-production, waste from waiting time, transportation waste and waste of motion, inventory waste and waste of product defects. Wu and Low (2008) found that in the production process of precast concrete products, there are many non-value adding activities, such as an efficient site layout, high set-up times of the manufacturing process, etc. These types of waste consume energy and generate unnecessary carbon emissions which can be avoided with appropriate management. When the process tree of the precast concrete product is examined from a lean perspective, many non-value adding activities are identified. These non-value adding activities are shown in Table 4.

As can be seen from Table 4, there are three groups that these non-value adding activities can be grouped into, including:

1. *Waste of finished products.* This category of waste is caused by the large inventory in the precast concrete factory, as well as the damages during handling.
2. *Waste of raw materials.* This category of waste is caused by the large storage area in the precast concrete factory, as well as the damages during transferring activities.

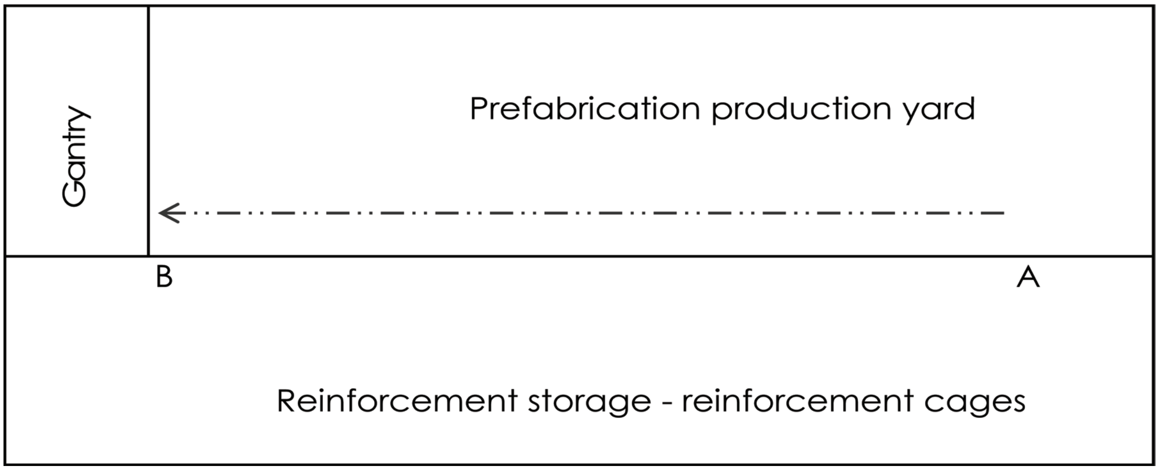
TABLE 4. Non-value adding activities identified in the production process.

Category	The amount of carbon emissions ($kg\ CO_2$/ column)
Waste of finished products	**18.29**
• Too much inventory in factory	
• Damaged products during inventory	
• Damaged products when handling	
• Double-handling or delivery due to unsatisfied quality or specifications	
Waste of raw materials	**9.29**
• 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	
Inappropriate production arrangements	**9.933**
• 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	0.003
• Double-handling or delivery due to unsatisfied quality or specifications	0.09

(Source: Wu and Low, 2011)

3. *Inappropriate production arrangements.* This category of waste is caused by the lack of lean thinking in the production management practices, such as:
    - Improper specification of building materials. Due to changes to the specifications, six previously manufactured precast concrete columns were abandoned.
    - Transportation is not taken into consideration. The overlapping of delivery times of different raw materials caused the delivery vehicles to idle in the precast concrete factory.
    - Unnecessary materials handling. As observed in the precast concrete factory, 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 3. This unnecessary back and forth movement was caused by apathetic employees and the lack of a written production manual.

FIGURE 3. A type of unnecessary movement in the precast concrete production process. (Source: Wu and Low, 2011)



RESULTS

The carbon emission values caused by these interruptions are recorded and shown in Table 4. As stated earlier, the embodied carbon of the precast concrete column was estimated to be 647.10kg CO_2 per column. In carbon labelling programs, this level of information is usually provided in the descriptive text for the products. For example, if the product is certified by the Singapore Green Labelling Scheme (SGLS) initiated by the Singapore Environment Council, the green label shown in Figure 4 will be used.

The customer can therefore compare the carbon emission values between different precast concrete columns and choose the column with lower carbon emission value. However, it should be noted that although carbon labelling programs can offer accurate estimation of the embodied carbon of construction materials, it lacks a benchmark to identify how efficient the

FIGURE 4. The green label for the precast concrete products in SGLS. (Adapted from: Singapore Environment Council, 2010)

production is. More importantly, the single score used in carbon labelling programs seems to be insufficient to support the principles of completeness, consistency and transparency in the PAS 2050 guidelines. As explained in Figure 1, there are two levels of benchmarking, which are short-term and long-term benchmarking. Current carbon labelling programs can offer a short term benchmark between different precasters. 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_2 is emitted per precast concrete column. An amount of 37.51 kg CO_2 is saved by applying the lean concept in the precast concrete factory and this amount is the lean score for the column. Such information should be provided in the carbon labelling programs to indicate the improving potential of the product. For example, if certified by the SGLS, the revised green label, which is shown in Figure 5, can be used.

Unlike normal carbon labelling program which highlights the inputs and outputs by design specifications, this lean score advocates refining the production process from a lean perspective. This can enhance the credibility and increase the comprehensiveness of the ecolabel information. Therefore, if two products are examined with similar carbon emission values, the customer can choose the one with lower lean score, because the production system of this product seems to be more efficient and the product may be more credible in the perspective of environmental performance.

When issuing the lean score for the precast concrete products, the continuous improvement plan cannot be overlooked. One of the most important instruments in lean production is believed to be Kaizen or continuous improvement, that is to say, production processes with "continuous improvement" plans should have better scores than those without such plans. In practice, it is proposed that a symbol of "+" or "–" be used next to the lean score to indicate this level of information for this product. As can be seen in Figure 5, if the manufacturer of this precast concrete product has a continuous improvement plan, a symbol of "+" is used next to the lean score to indicate this level of information.

FIGURE 5. The revised green label for the precast concrete products in SGLS. (Adapted from: Singapore Environment Council, 2010)

GreenLabel SINGAPORE

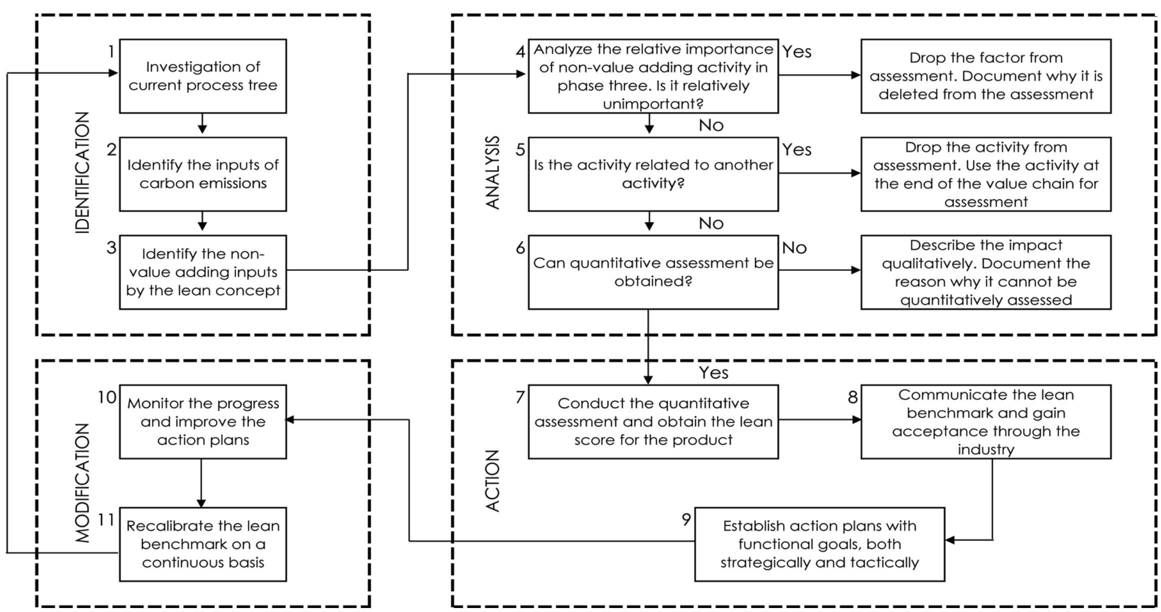
Eco Friendly Building Material
SGLS User Agreement Number: xxxx
Recycled Content: xx%
Carbon Emission Value: 647.10 CO_2 kg/column
Lean score: 37.51^{+} CO_2 kg/column or $5.80\%^{+}$ of the carbon emission value

THE GENERAL FRAMEWORK

Following the three processes explained earlier, the applicability of the lean concept in carbon labelling program for precast concrete products can therefore be summarized into the four phases as illustrated in Figure 6. These four phases are:

1. *Identification.* In this phase, the production process tree used in the LCA study is refined by the lean concept to identify the true valuable inputs. Non-value adding activities, or interruptions to the production process are identified and eliminated from a lean perspective in order to provide the lean benchmark. This can be completed by applying the VSM tools. It should be noted that the identification of interruptions should be conducted by employees with lean thinking. There are many activities that are considered as normal activities, but should be categorized as interruptions examined by the lean production philosophy, such as storage, bufferstock and transferring activities. In practice, it is proposed that a "Kaizen" team, who will conduct visual observations in the production site using VSM and basic tracking tools, should be involved when conducting the identification process.
2. *Analysis.* Carbon emissions caused by the interruptions identified in phase one is calculated in this stage. Both quantitative and qualitative method should be adopted. For non-value adding activities which involve energy consumption and raw materials, quantitative calculation should be provided. On the other hand, for evaluating the impact of issues that are difficult to quantify (e.g. continuous improvement and top management commitment), qualitative evaluation of the impact should be conducted. In addition, in order to capture the influence of the frequency of the interruptions, the relative importance of the interruptions are identified in step 4, as shown in Figure 6. Relatively unimportant interruptions will therefore be dropped from the assessment.

FIGURE 6. Lean benchmarking process in carbon labelling programs.



3. *Action.* A corresponding lean benchmark associated with the lean score should be obtained in this stage to provide a relative measurement about the performance of the materials towards environmental sustainability. The interruptions that have been identified in stage 2 can be used for the manufacturers to improve the production performance. For example, as listed in Table 4, these interruptions can be used to help the precast concrete manufacturer to improve the production performance. A "continuous improvement" plan to help the materials improve towards the benchmark should be prepared as well.
4. *Modification.* As technology improves and the production process refines, the lean score and the action plan 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.

DISCUSSIONS

In an industry as complex as construction, a wide range of raw materials are used in a number of different applications (Construction Industry Research and Information Association, 1995). The lean benchmarking process is designed for precast concrete products at the start because of the origin of the philosophy i.e. 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 to the precast concrete industry will require few modifications of the lean concept.

However, the origin of the lean concept does not preclude applying the lean concept to the carbon labelling programs 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 precast concrete products and other construction materials.
3. The carbon labelling programs designed for precast concrete products and other construction materials are the same. These programs use LCA as the evaluation approach. Therefore, the carbon labelling programs 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 for 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 more transparently and accurately indicated.

In addition, it should be noted that there are a few issues that may influence the accuracy of the lean score. For example, some interruptions to the work flow do not always happen in the production process. In this case, rejection of materials due to unsatisfied quality happened twice in the contract period, which is half a year. The calculation of the lean score should therefore be designed to capture the influence of frequency of such interruptions. In addition, extreme care should be paid when investigating the continuous improvement plan of the manufacturer. Such investigation should be conducted by persons who are familiar with the lean concept and the problem of point chasing in the labelling programs can be avoided.

CONCLUSIONS

The environmental assessment programs, including carbon labelling programs should evolve through time to continually provide the link between environmental information and the decision-making in the construction industry. Current carbon labelling programs have drawbacks in being able to truly identify the environmental impacts. The inputs of energy and resources required in the LCA study are sometimes generated from the design specifications and production operations. Two outcomes resulted from this practice cannot be overlooked. The inputs of resources and energy may be larger due to either waste of materials or damages of finished products. In addition, the score obtained from the labelling program does not represent how much the product should impact the environment. In other word, the current labelling program provides some level of benchmarking for short-term comparison, while the long-term benchmarking is somehow missing.

The lean production philosophy can be adopted in the precast concrete industry for precasters to refine the production process, based on which a lean benchmark can be created. This lean benchmark provides the improving potential that can be achieved by the precaster and can be used to address a few problems that are brought about by using LCA principles and techniques. It can be used to enhance the credibility of the ecolabel by providing information related to waste of raw materials, damages to finished products and inappropriate production arrangements. It can also be used to increase the comprehensiveness of the ecolabel information by creating a lean score rather than a single sign. More importantly, the lean concept advocates the idea of "continuous improvement" that new innovative technologies and companies with improving plans should fare better in the labelling programs. The principles of completeness, consistency and transparency are all enhanced by introducing the relative measurement to the assessment criteria. A general framework is proposed in this paper for precasters to conduct the lean benchmarking process and calculate the lean score. Based on both absolute and relative measurements of carbon emissions for construction materials, consumers can choose the truly environment-friendly materials and the construction industry can then move closer towards being a "green" industry.

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