RESEARCH

COMPARATIVE CARBON FOOTPRINT ANALYSIS OF BAMBOO AND STEEL SCAFFOLDING

Paul F. Laleicke[1], Alex Cimino-Hurt[2], Dylan Gardner[3], Arijit Sinha[4]

ABSTRACT

Building construction and maintenance is one of the major contributors to global warming and as a result has the potential to be a leader in sustainable development. Scaffolding systems are an important component of building construction, especially high-rise buildings. A scaffold consists of a modular system of metal or bamboo tubes or pipes. Scaffolding is a temporary construction structure created for reaching heights above a human's reach, with the purpose of helping in construction or maintenance of a structure. The scaffolding industry in the US is dominated by steel. In areas where bamboo is indigenous, like many East Asian cities, bamboo is the scaffolding material of choice, even when it comes to high-rise buildings. Our goal was to analyze bamboo and steel thoroughly and establish their environmental impacts using life cycle analysis (LCA). Consequently, this study explores the ecological viability in expanding the use of bamboo scaffolding where steel predominates. The functional units used in this study are bamboo and steel scaffolding systems that are 2.74 m high, 2.49 m wide, and 1.21 m deep. A cradle-to-gate LCA was performed to evaluate the environmental performance of the two scaffolding systems. Our results suggest that bamboo scaffolding has a lower carbon footprint than steel scaffolding, with an ability to sequester carbon during its growth phase being a significant contributing factor. This is an important advantage of bamboo over nonrenewable materials (steel). Additionally, bamboo functions as a buffer, delaying the release of CO_2 after the use phase. The main challenge for any scaffolding system made from renewable materials in the western world is the demand for standardization. Therefore, an ideal future goal should be the design of standardized scaffolding systems using renewable materials that combines the durability and homogeneity of steel scaffolding with the sustainability and environmental performance of bamboo scaffolding.

KEYWORDS

life cycle analysis, sustainability, green building, cradle-to-gate

1. Graduate Research Assistant, Dept. of Wood Science and Engineering, Oregon State University
2. Graduate Research Assistant, Dept. of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University
3. Undergraduate student, School of Civil and Construction Engineering, Oregon State University
4. Assistant Professor, Dept. of Wood Science and Engineering, Oregon State University

INTRODUCTION

In engineering, sustainable design is a design ideology that supports and facilitates sustainable economic, human, and environmental development. In this study we define sustainability as the process of designing and directing development in the present in such a way as to ensure equal access to resources and opportunities for future generations (UN 2010). Construction is an important application area for sustainable principles. Sustainable construction practices incorporate ecological principles, with minimal environmental impacts, utilizing natural and renewable materials, while providing consideration towards disassembly.

In terms of material used, the construction industry is one of the major consumers of materials extracted out of the Earth's crust (Sinha et al. 2013), accounting for about 24% of global extractions. Another disconcerting fact is the reliance on fossil fuels. More and more evidence shows that excessive consumption of fossil fuels leads to climate change, of which the most influential factor is carbon emission (EPA 2013). In China, for example, construction industries consume about 40% of the natural resources, representing 20% to 30% of the national energy requirements and 30% to 40% of all the urban materials generated (Kaian 1999; Press 2010, Sinha et al. 2013). Embodied energy of a building typically accounts for 20% of its energy use during a 50-year life cycle and is equivalent to 10 to 20 times its annual energy use (Sharma, et al. 2011). Therefore, it is necessary to study the energy and carbon flows over the life cycle of a building and develop strategies for their reductions in energy use and carbon emission. At present, life cycle assessment (LCA) is used as a tool to assess the environmental impacts of product systems and services, accounting for the emissions and resource consumption during the production, distribution, use, and disposal of a product. Applying LCA to buildings allows us to see which phase of a building's life cycle and which type of building consumes more energy and has more greenhouse gas emissions (Sharma, et al. 2011) There is growing interest in sustainable assessment at various levels and severities in today's society. The role played by the concept of life cycle analysis and, even more, the advancement of LCA structure and methodology, has broadened the idea of sustainability to include social and economic impacts.

An important component of building construction is scaffolding. A scaffold consists of a modular system of metal or bamboo tubes or pipes. Scaffolding is a temporary construction structure created for reaching heights above a human's reach, with the purpose of helping in construction or maintenance of a structure. A scaffold is usually made from steel, bamboo, and lumber, or a combination of these materials. The designs can range from relatively simple to rather complex; this is more specific to the bamboo scaffolding design as bamboo requires more cross bracing. Due to the round cross sectional shape of bamboo, it is difficult to make connections of bamboo to create a tall or wide structure. Indigenous knowledge of the material and its limitations have allowed East Asian cultures to develop connection types to be used in a bamboo scaffolding unit safely with a long history of adequate and safe performance (Chung and Yu 2002). Unlike Asia, in the US bamboo scaffolding is not popular and is seldom used.

The U.S. Department of Labor Occupational Safety and Health Administration (OSHA) has specific standards for the construction and use of scaffolding in the workplace. OSHA lists the requirements for what a scaffold consists of and what qualifications it must meet. Each scaffold and its component shall be capable of supporting, without failure, its own weight and at least four times the maximum intended load applied or transmitted to it (OSHA 1910.28 D). The scaffolding industry in the US is dominated by steel. In areas where bamboo is indigenous, like many East Asian cities, bamboo is the scaffolding material of choice, even when it comes to high-rise buildings. This study explores the ecological viability in expanding the use of bamboo scaffolding. The goal was to analyze bamboo and steel thoroughly using life cycle analysis and establish their environmental impacts.

METHODS

Life Cycle Assessment (LCA) is a tool used to identify the inherent impacts a product and its manufacturing have on the environment, society, and economy. There are three standard forms of LCA; baseline, comparative, and streamline, which are normally comprised of four steps. The first two steps, 'goal and scope', and 'Life Cycle Inventory' are the standard steps fulfilled in most LCA's while the next steps, 'Life Cycle Impact Assessment', and 'Interpretation' are carried out less often. LCA can be used in a variety of ways making it a robust tool; however, there isn't quite a universally recognized template that incorporates all four steps. This LCA will use the structure provided by the ISO 14040 series to analyze the comparative impacts of bamboo and steel scaffolding. We hope that the results of this LCA will affect a change in the lack of parity between bamboo vs. steel scaffolding use in the Western world.

Goal and Scope

This study explores the viability in expanding the use of bamboo scaffolding in areas where steel scaffolding predominates. We evaluated bamboo and steel scaffolding systems thoroughly to established their environmental impacts and perform a comparative analysis.

This LCA takes a cradle-to-gate scope of the respective scaffold processes. The 'gate' in this case looks at the steel and bamboo materials up until ten construction/deconstruction cycles of a scaffolding system. The impact this study focused on is the Global Warming Potential (GWP) expressed in mass of carbon dioxide (CO_2) equivalent. The target groups were Hong Kong construction companies. Bamboo scaffolding data was collected from this region in order to accurately represent their impacts in a fully industrialized setting. This LCA is limited in scope to account for GWP and no attempt was made to quantify the social impacts of the use of both material and its cultural significance. To capture the cultural dimension a social LCA is required with thorough understanding of the interdependence of the use of material and indigenous culture, which was beyond the scope of this study.

This study has a few assumptions, of which some were based on data availability. First, it is assumed that bamboo scaffolding production can be sourced within a 500 km radius of a representative construction site. Second, it is assumed that both the steel and bamboo are produced in China. Third, it is assumed that Chinese steel production can be conservatively modeled with US steel industry figures. Fourth, it is assumed that the proposed functional unit would perform equally and adequately compared with the durability of the different scaffold system. Finally, it is assumed the processes that we identified represent a majority of the impacts coming from production.

BAMBOO

Bamboo is typically associated with the history, culture, and construction in Asia dating back 5,000 years (Tong 2001). To investigate the inputs and outputs of carbon dioxide from a functional unit of bamboo scaffolding, several considerations regarding the material had to be made.

Functional Unit (FU)

The design of the functional unit (FU) accounts for the specific performance requirements for the design and construction of bamboo scaffolding. The design of the functional unit is one of various types presented in the official guidelines on the design and construction of bamboo scaffolds (HKBD 2001). It is 2.74 m high, 2.49 m wide, and 1.21 m deep. Each of the standardized design schemes is professionally engineered. Alternative types that could be necessary to meet the requirements of a construction site require the participation of a design engineer (HKBD 2001). Any type of work that is related to the erection, maintenance, and disassembly of the scaffolding requires supervision by a specifically trained worker. The double-layered bamboo scaffold (DLBS) is similar to European and North American standardized types of steel scaffolds. The working platforms are fixed between two layers, the finishing (inside) and the outer (outside) layer (Tong 2001). It mainly consists of two bamboo species, *Phyllostachys pubescens* and *Bambusa pervariabilis*, referred to as Mao Jue (Moso) and Kao Jue, respectively.

Figure 1: Functional Unit Bamboo

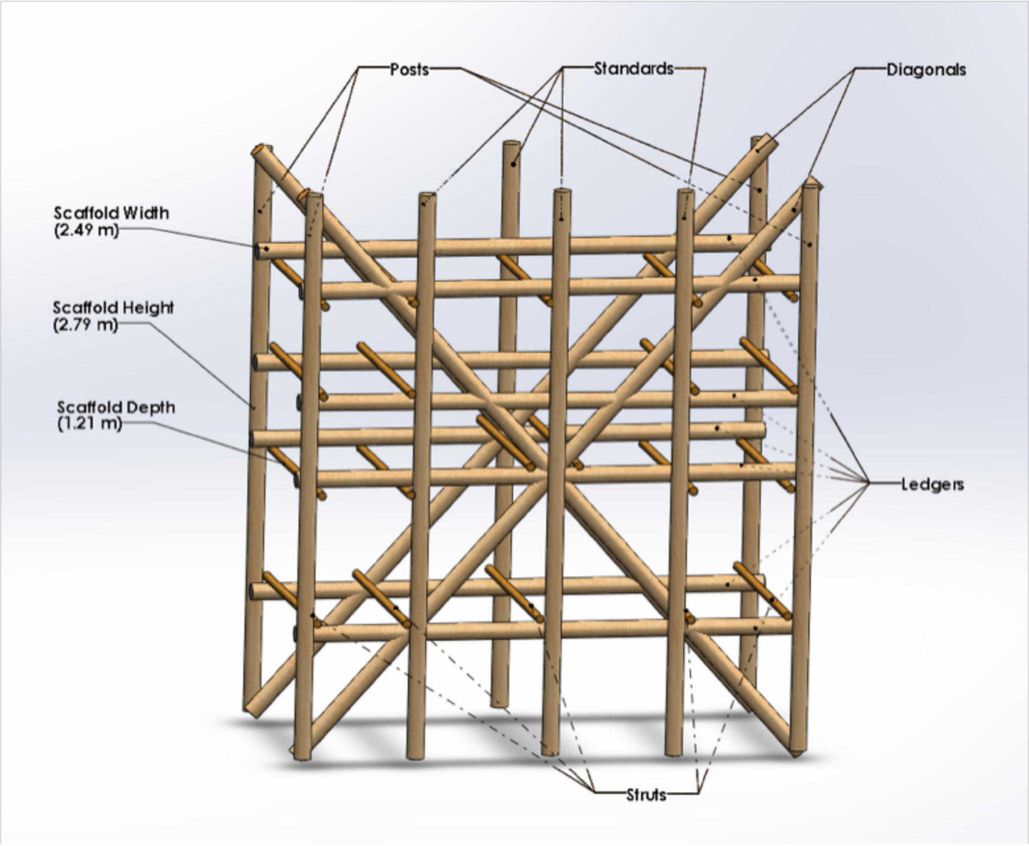


Table 1: Calculation of Bamboo-Mass-Volume per Functional Unit

Element	Species	Function Amount	Wall-Thickness (mm)	External Diameter (mm)	Overall Area (m^2)	Inner Area (m^2)	Massive-Ring-Area (m^2)	Volume (m^3)
Post	Mao Jue	4 X h	10	80	0.005	0.0028	0.0022	0.024
Diagonal	Mao Jue	4 X SQRT(h^2+w^2)	7.5	80	0.005	0.0033	0.0017	0.025
Strut	Kao Jue	20 X d	5	40	0.001	0.000070	0,00093	0.022
Ledger	Mao Jue	8 X w	7.5	80	0.005	0.0033	0.0017	0.033
Standard	Mao Jue	4 X h	7.5	80	0.005	0.0033	0.0017	0.018
Sum								**0.122**

The volume of the actual bamboo substance in one functional unit was calculated using the geometry of the material. As shown in Table 1 The quantity of different elements was determined from the draft of the functional unit and expressed as a multiple of either height (h), width (w), or depth (d). The wall-thickness and external-diameter were taken as an average from (Chung and Siu 2002).

The volume of bamboo used in one functional unit is 0.122 m^3. The density of bamboo is 600 kg/m^3 (Albermani, Goh and Chan 2007). Therefore, the mass of bamboo can be assumed as 73.2 kg per functional unit.

Table 2: Process Chart of Bamboo and Steel listing all the major processes in manufacturing and use of one functional unit of bamboo and steel scaffolding systems (GHG = Green House gases).

Bamboo	*Input*	*Output*	*Steel*	*Input*	*Output*
Plantation	Energy (Sunlight)	Emissions (GHG ,O_2)	Sintering	Energy (Coal)	Emissions (GHG)
			Cokemaking	Energy (Natural Gas)	Emissions (GHG)
			Pulverized Coal Injection	Energy (Coal)	Emissions (GHG)
Harvest Operation	Energy (Fossil Fuel)	GHG	Ironmaking	Energy (Coke)	Emissions (GHG)
			BOF Steelmaking	Energy (Natural Gas)	Emissions (GHG)
			Hot Rolling	Energy (Natural Gas)	Emissions (GHG)
			Cold Rolling	Energy (Electricity)	Emissions (GHG)
Conditioning	none	GHG	Tempering and Finishing	Energy (Natural Gas, Electricity)	Emissions (GHG)
Transportation	Fossil Fuel	GHG	Transportation	Energy (Fossil Fuel)	Emissions (GHG)
Use	Bamboo Replacement	None	Use	Energy (Fossil Fuel)	Emissions (GHG)

The production of bamboo for scaffolding is a five-step process. Beginning with a plantation-phase, the bamboo has to grow until it reaches the required dimensions. As no additional efforts are considered, the only input is sunlight that is required to provide the energetic base for photosynthesis. The corresponding output is O_2.

The subsequent phase considers harvest operation. Fossil fuel is required for the operation of harvest machinery and tools, resulting in an output of CO_2.

Drying and conditioning, to optimize the mechanical properties of the poles and minimize internal stresses, is done in the so called conditioning phase. This treatment of the bamboo is traditionally done over several weeks, without the contribution of artificial heat and climate. The poles are air-dried in a vertical position for about three months (Jian 2008). No in and output of carbon dioxide can be accounted for in this phase. As no further processing of the poles is required after conditioning, the bamboo is transported to construction sites by the use of trucks. This requires an input of fossil fuels and results in an output of CO_2.

The use-phase is the last step in the process and requires continued input of bamboo poles to replace any bamboo that has failed. As the system borders limit further consideration, bamboo residues and waste are not taken into account.

$$\mathbf{73.2\ \frac{kg}{FU} * -1.83 \frac{CO_2}{kg} + -133.96\ kg * 0.67\ \frac{kg\ root}{kg\ culm} = -223.7 \frac{kg\ CO_2}{FU}} \quad [1]$$

$$\mathbf{10 * 0.3 * (-223.7\ kgCO_2) + (2.0\ kgCO_2) + (23.86\ kgCO_2) = -593.5\ \frac{kg\ CO_2}{FU}} \quad [2]$$

To quantify the flows of CO_2 connected to a functional unit of bamboo scaffolding different calculations for each of the phases were conducted. Selected formulas and corresponding calculations are shown in Eq. [1].

The amount of CO_2 that is sequestered and stored during the growing and life phase of bamboo was calculated with the use of two factors obtained from van der Lugt et al. (2012). The carbon that a bamboo functional unit sequesters is assumed to be the equivalent to 133.96 kg of CO_2. The amount of CO_2 stored below the ground equates to around 2/3 of the overland sequestered carbon (van der Lugt, et al. 2012). Thus, the total amount of bamboo that is needed to build the functional unit is responsible for the sequestration of 223.7 kg of CO_2.

Harvest operation includes the use of chainsaws and other machines that can be used independently. The quantity of CO_2 released to the environment was determined by the ratio of a functional unit to the weight of the bamboo scaffolding of this analysis (van der Lugt, et al. 2012). After applying the present mass of a functional unit to the calculation, an amount of 0.873 liters of gasoline is used to harvest the functional unit of 73.2 kg of bamboo. This results in a release of 2 kg of CO_2 per functional unit. As mentioned above, no inputs and outputs are considered for the conditioning phase.

Construction sites are usually situated in urban areas. Sources and collecting sites for bamboo are usually outside those areas. Evidence to generate a reasonable value for the distance between the source of the material and the construction site is not available. The amount of CO_2 emission for the transportation of one kg of bamboo scaffolding is based on the same quantity of CO_2 emitted for the transportation of one kg of steel scaffolding. While the distance from transportation to the manufacturing facility is assumed to be 30 km in the publication, a greater distance is assumed here. To emphasize the transportation emissions, a distance of 500 km is taken into calculation. This number can be assumed to represent realistic distances in China that can be related to the origin and destination of bamboo.

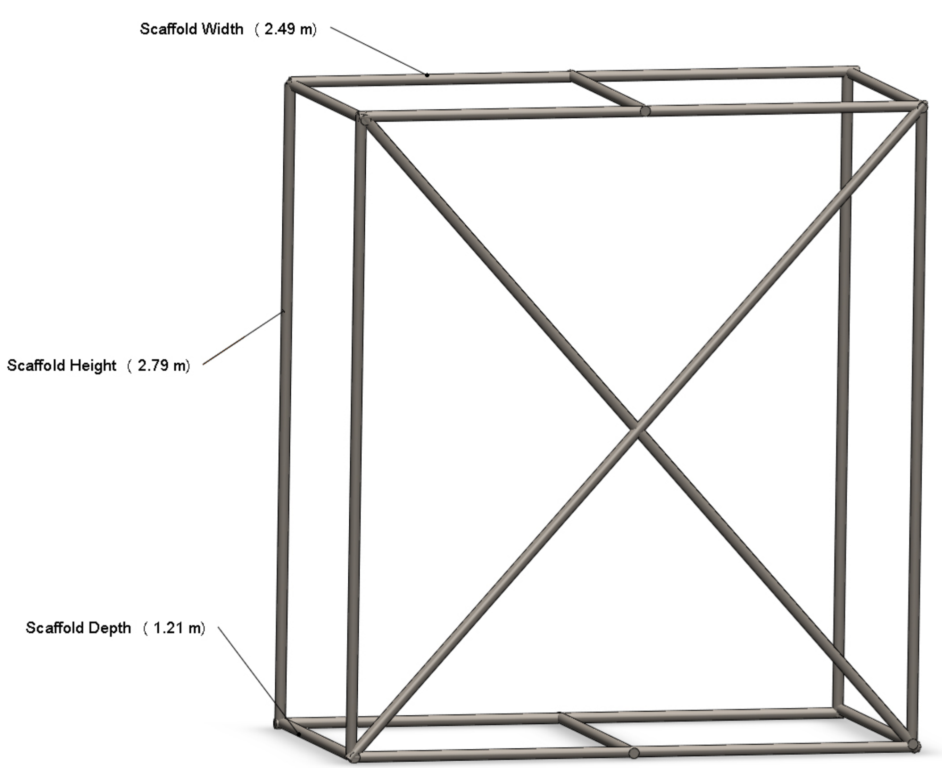
To calculate the carbon dioxide emission during the use phase, a simple assumption was made. For every time the functional unit of bamboo scaffolding is utilized, one third of the unit needs to be replaced. Degradation of the bamboo due to climate is an important factor that limits the reuse of bamboo culms (Francis 2001). Two thirds of the initial functional unit can be transferred to an adjacent construction site. For this reason, one third of the carbon dioxide trade of the plantation, harvest operation, conditioning, and transport to the construction site needs to be added to the outputs of the use phase, as new culms are utilized to replace the old ones. To show and stress the influence of this assumption, the presented calculations are multiplied by 10 utilizations (eq. [2]).

STEEL SCAFFOLDING

Functional Unit

The functional unit of steel scaffolding is shown in Fig. 2. This scaffolding arrangement (Fig. 2) is comparable in arrangement to the bamboo functional unit. Steel scaffolding typically has a diameter of 48.3 mm and a mass per length of 4.4 $kg*m^{-1}$ (SteelPipes 2013). The other dimensions of steel can vary greatly depending on application. In order to maintain a functional comparison we assumed the same outer dimension for the steel scaffolding and used the above arrangement to determine piece count.

Figure 2: Functional Unit Steel



The dimensions and mass of steel functional unit are presented in Table 3. Accounting for steel involved the examination of the cradle-to-gate, gate-to-gate, and gate-to-use stages of steel scaffolding. As shown in Table 2 the production of steel consists of various steps in each of the different life cycle stages. In the cradle-to-gate portion, hematite is mined from open pits and then heated in a process called sintering where iron ore briquettes are formed. These briquettes are fed into another oven where pulverized coal is injected and burned to remove oxygen from the ore. The product of this process is metered into a blast furnace heated by coal coke and iron is collected from the bottom via a kettle. The iron collected in the kettle is used in Basic Oxygen Furnace (BOF) steel production where air and heat are used to drive out impurities from the steel and other additives are added to produce the physical and chemical properties desired in the final product.

Table 3: Dimension and Mass of Functional Unit Steel

Functional Unit	Height	Length	Depth	Diagonal
Units	(m)	(m)	(m)	(m)
Functional Unit Dimensions	2.74	2.49	1.21	3.70
Quantity	4	4	6	2
Subtotal	11.0	9.96	7.26	7.4
Grand Total	35.6 m			
Mass of steel/meter	4.4 kg/m			
Mass of Functional Unit	**156.6 kg**			

The next stage, gate to gate, involves the physical forming of the raw steel material into the components of functional unit scaffolding. The hot rolling process is used to form the raw material into sheets before the material has fully cooled. The steel is kept hot with a combusted natural gas in this process. After the material is relatively cool, it is stretched and shaped into tubes via the cold rolling process. Electricity is used to draw the steel into the desired shape in this process. Once the steel has been rolled into its desired form it is heated and cooled in a process called tempering in a fluid to restructure the surface steel into a desired crystal structure. The final product is finished after undesired extra bits are ground off. The summary of calculated greenhouse gas potential for each stage of steel manufacturing process is presented in Table 4.

Calculations

The CO_2e impact for the stages from mining through tempering and finishing were taken from figures provided by the U.S. DOE in a study profiling the iron and steel industry. The stages and their corresponding quantities of CO_2 for one functional unit are shown in Table 3. This study offers a 1998 estimate of the pounds CO_2 per ton of steel produced in all the primary steel production steps. The steps accounted for above were chosen as a best estimate of the processes involved in the production of the steel tubes used in steel scaffolding. Production of

Table 4: Steel Carbon Impact per Life Cycle Stage

Stage	kg CO_2e / FU
Mining	5.41
Cokemaking	8.01
Pulverized Coal Injection	0.08
Ironmaking	156.9
BOF Steelmaking	38.44
Hot-rolling	29.51
Cold-rolling	17.97
Tempering and Finishing	13.73
Transportation	2.70
Use	27.28
Total	**300.1**

the steel tubes and joints involve two different forms casting that are approximated using the emissions associated with hot-rolling and cold-rolling. The pounds CO2 per ton steel is converted to kg CO2e per FU in the conversion demonstrated through equations [3-5].

Mining Stage Carbon Impact

$$\frac{69\ lb\ CO_2}{1\ ton\ steel} \times \frac{1\ kg}{2.20\ lb} \times \frac{1\ ton}{907.19\ kg} \times \frac{156.6\ kg}{1\ FU} = \frac{5.41\ kg\ CO_2}{FU} \quad \textbf{[3]}$$

Transportation Carbon Impact

$$\frac{1\ gallon\ diesel\ fuel}{202 miles \cdot 1\ ton\ steel} \times \frac{22.38\ lb\ CO_2}{1\ gallon\ diesel\ fuel} \times \frac{1\ kg\ CO_2}{2.20\ lb\ CO_2} \times \frac{1\ ton\ steel}{907.19\ kg\ steel} \times \frac{1\ mile}{1.61\ km} = \frac{3.45 \times 10^{-5}\ kg\ CO_2}{km \cdot kg\ steel} \quad \textbf{[4]}$$

$$\frac{3.45 \times 10^{-5}\ kg\ CO_2}{km \cdot kg\ steel} \times 500\ km \times \frac{156.6\ kg}{1\ FU} = \frac{2.70\ kg\ CO_2}{FU} \quad \textbf{[5]}$$

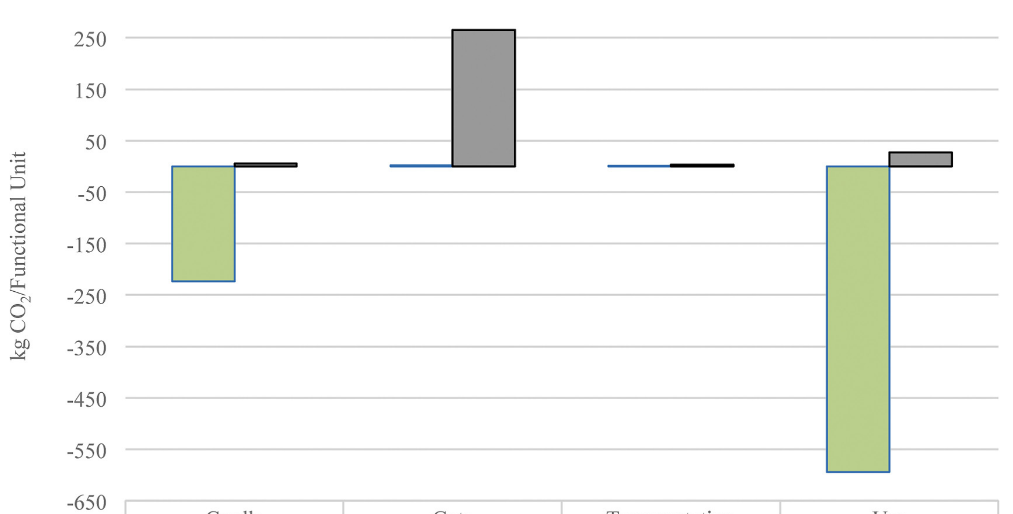
Transportation of steel was calculated using the assumed 500 km total transportation distance, the freight efficiency of train transportation, and the fuel emissions impacts of diesel. A freight fuel efficiency of 202 mile-tons per gallon of diesel is used (shipping comparisons 2013). The use phase is calculated as described above with bamboo except instead of bamboo's 1/3 replacement rate we use a 1/10 replacement rate to appropriately account for the relative durability of steel. This table is a very simple view of the impacts of steel production. All along the process, other effluents and waste production are present that contribute to environmental degradation.

COMPARISON

In order to perform a side by side comparison of the two scaffolding systems, we organized and grouped the life cycle impacts into four stages: Cradle, Gate, Transportation, and Use. Fig. 3 illustrates the relative impacts for bamboo and steel, clearly demonstrating the sequestering nature of bamboo and the high emissions nature of steel. During the cradle stage, i.e., growing of bamboo and mining of ore for steel manufacturing, the environmental impacts of mining is higher than that of a plantation of bamboo, which produces negative impacts due to carbon sequestration (Fig. 3). Manufacturing of steel is an energy intensive process and consequently results in the highest equivalent CO_2 emissions across all four stages considered as seen from Fig. 3. Emissions resulting from the transportation of bamboo are slightly higher than those corresponding to steel.

The results of our study, however, clearly demonstrate the importance of system boundaries and assumptions. Had we included the end of life for bamboo and steel, bamboo might not have looked as "green". Steel can be recycled which offsets further demand for steel but bamboo cannot. It must either go to the land fill or be burned. If it is burned for energy

Figure 3: Side by Side Comparison of environmental impacts for various stages bamboo and steel scaffolding life cycles



	Cradle	Gate	Transportation	Use
Bamboo	-223.7	2	1.26	-593.5
Steel	5.41	264.7	2.70	27.3

purposes, it could possibly be used to offset the use of natural gas or fossil fuels for energy production. Similarly, one of the most critical assumptions in this study relates to the carbon sequestration properties of bamboo. If carbon sequestration were not accounted for, our results would have been different.

INTERPRETATION

The collection of data for both materials and especially for the functional unit in the context of scaffolding was not as easy as assumed. Scaffolding has been in development as a tool for the construction industry for centuries, and has changed based on the materials at hand. The world seemed to settle on two commonly used scaffolding materials: bamboo and steel. Through the LCA methods introduced in ISO 14040, we were able to construct a study that compared the environmental influences of bamboo and steel scaffolding.

Fig. 3 depicts the CO_2 emissions per functional unit of steel and bamboo scaffolding. The impression the graphical representation presents deserves further scrutiny. The 'use' category is somewhat misleading as it doesn't take into consideration the end of life scenario of the bamboo, which leaves the bamboo side with a large amount of sequestered carbon (just from the plant mass) and no carbon release. Within the scope of this LCA it is clear that bamboo is less environmentally detrimental than steel scaffolding. Changing the parameters perhaps would render different proportions of GWP per process, but would most likely favor bamboo, even if the study took into consideration the carbon release of the bamboo material.

This LCA's data was sourced from literature because of lack of access to database information for these processes as they occur in China, logistics, and resources. Having access to relevant databases is recommended for future studies in this area and having access to a relevant database would allow the results to be more accurate and comparable between materials. Regardless, this study shows that there is a case for the introduction of bamboo on a broader scale. The potential environmental advantages of bamboo scaffolding implementation may outweigh the possible health or legal impacts that come with bamboo scaffolding, and should be thought of as a comparable material to steel in that regard.

Unrepresented in this study are other ecological impacts associated with the mining of the ores required for steel production. We expect that a study that considers more environmental impact indicators would only accentuate the differences in these two materials as they perform in China. The adoption of bamboo scaffolding systems in the United States would have to confront at least two immediate problems. Should the bamboo be sourced from China, as many materials are these days, the transportation associated with shipping it across the ocean may greatly affect its environmental performance. And should bamboo be grown locally to meet a demand for scaffolding, thus offsetting some transportation impacts, an LCA may be inadequate in assessing the full environmental impacts. Bamboo is not a native species to the Western hemisphere and its widespread introduction could result in land use issues, which can't be accounted for in a product LCA. Regardless, our study shows strictly from an environmental standpoint that using bamboo scaffolding is beneficial.

CONCLUSION

The results of this study show that the ability of renewable material (bamboo) sources to sequester carbon during their growth phase is an important advantage over non-renewable materials (steel). Additionally, bamboo functions as a buffer, delaying the release of CO_2 after the use phase.

A main disadvantage of steel based scaffolding is the vast amount of CO_2 emissions during the production phase. Most of the natural processes to grow bamboo are integrated in different material flows and cycles, eliminating any significant output of emissions. Emissions from any end of life utilization of bamboo are not considered in this study. Nevertheless, this can be an important factor to consider the overall CO_2 emissions to compare steel as a recyclable and bamboo as a renewable material.

The main challenge for any scaffolding system from renewable materials is the demands of standardization in the Western world. Therefore, an ideal future goal could be the design of standardized scaffolding systems on the basis of renewable materials that combine the durability and homogeneity of steel scaffolding with the sustainability and environmental aspects of bamboo scaffolding. Such a system has been successfully used in the past in Hong Kong (HKPU CSE 2014). There is a pressing need, then, to design such a hybrid system for the Western world.

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