A GREEN-LEAN SIMULATION MODEL FOR ASSESSING ENVIRONMENTAL AND PRODUCTION WASTE IN CONSTRUCTION

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ABSTRACT

Lean production principles are well known with documented savings and productivity enhancements through the elimination of waste in construction. Several researchers claim that lean can promote sustainability in production systems. More precisely, sustainable or "green" practices seem to be a natural extension of the lean philosophy at an operational level. Green construction also seeks to reduce waste of energy, water and materials used during construction. Different studies show how the lean and green approaches share many of the same best practices to reduce wastes.

From the standpoint of waste minimization – a common concept of both lean construction and green construction – this paper explores the relationship between lean and green, highlighting opportunities to enhance environmental and production performance by implementing green-lean practices in construction. Thus, an integrated green-lean simulation model of a construction project as a case study is proposed. Discrete-Event Simulation (DES) is used as the modeling strategy in this research, given its powerful capabilities to quantitatively analyze complex construction operations. Environmental and production variables are simultaneously assessed in the same simulation model, and the environmental impacts from the implementation of green-lean practices are discussed. Preliminary results demonstrated not only better resource utilization and improved time cost performance, but also energy savings and decrease of greenhouse gas emissions in the project.

KEYWORDS

Environment, Green Construction, Lean Construction, Waste, Discrete-Event Simulation.

INTRODUCTION

Waste in the construction industry has received much attention by construction researchers and practitioners (Rahman et al., 2012; Viana et al., 2012). Traditionally, project managers tend to conceptualize "waste" as physical construction waste (Wong et al., 2012). From the lean construction standpoint, waste represents resources or activities that are time and cost consuming, but creates no value (Koskela, 1992). Therefore, there is noticeable waste in construction processes other than physical. Elimination of waste in a process is one of the main goals of the lean construction community (Al-Sudairi, 2007; Dunlop & Smith, 2004; Farrar et al., 2004; Mao &

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Zhang, 2008). Thus, lean is about the elimination of all non-value-added steps in a process. Lean principles are well known with documented savings and productivity enhancements through the elimination of waste in construction (Fliedner, 2008).

Several research efforts such as those conducted by the Environmental Protection Agency (EPA) seem to indicate that lean companies show significant environmental improvements by being more resource and energy efficient. Even more, it has been demonstrated that the implementation of lean principles not only produces significant production and environmental improvement but also a robust waste elimination culture. EPA claims that lean produces an operational and cultural environment highly conducive to waste minimization and pollution prevention which promotes sustainability in an organization (EPA, 2000).

Sustainability is the long term maintenance and enhancement of human well-being within finite planetary resources. It is usually considered to have environmental, economic, and social dimensions (Wentworth, 2012). It is argued that environmental considerations can be effectively integrated into lean methods to reduce waste, yield greater cost savings, and increase environmental benefits (Bantowsky, 2007). Therefore, the focus of sustainable or “green” construction is also on removal of waste from the construction process, and accordingly, this can provide the environmental dimension to lean construction. In this paper, the term “green” is associated with the environmental dimension of sustainability.

Although current lean and green approaches seemingly exhibit a disconnect between environmental and production waste management in construction (Rosenbaum et al., 2012), they naturally share a common goal: to eliminate as much waste as possible (Nahmens, 2009).

Different studies show how the lean and green approaches share many of the same best practices to reduce their respective waste. For instance, Bergmiller and McCright (2009) compared lean manufacturing approaches with green approaches to determine the degree of similarity that exists between the two and suggested that a model which integrates both into one comprehensive program focused on reduction of all wastes (those targeted by lean and those targeted by green) can be the most effective and efficient path to long-term organizational sustainability.

The “wastes” typically targeted by environmental management agencies are not explicitly included in the list of production wastes (transport, inventory, motion, waiting, overproduction, over processing and defects) that lean practitioners routinely target (EPA, 2003). Therefore, looking at the commonalities of the green and lean approaches allows researchers to understand the parallel structures of these models and to develop a comprehensive, integrated waste reduction model for the implementation of green-lean practices through one coordinated effort (Bergmiller & McCright, 2009).

Based on the potential benefits of using the integrated model to manage waste, the authors proposed a green-lean modeling approach to simultaneously assess environmental and production waste in construction using DES.

DISCRETE-EVENT SIMULATION

DES models describe systems evolving over time, where state variables change instantaneously at separate points in time (Law, 2007). The main goal of DES is to identify problem areas and quantify or optimize production system performance (Lind et al., 2009). DES is able to model and handle complex systems with highly dynamic decision rules and relationships between different entities and resources, and it explicitly includes system uncertainty (Law, 2007). DES has also been recognized as a powerful technique for the quantitative analysis of complex construction operations (Martinez, 2010). DES is not only able to model and represent the production system variables and patterns, but also the environmental (González et al., 2012). To consider the environmental impacts of a process, it is important that environmental parameters and process parameters are assessed simultaneously. DES is able to simultaneously assess the environmental and production variables in the same simulation model (González & Echaveguren, 2012).

In the last three decades, researchers have developed several simulation tools and engines to model and optimize construction operations (Halpin, 1976; Ioannou, 1989; Martínez, 1996; Marzouk & Moselhi, 2003; Shi & AbouRizk, 1997). However, the study of project's environmental effects has not received much attention in construction, except for some recent studies that have focused on the analysis of emissions in construction projects using DES modeling techniques and environmental models (Ahn et al., 2009; Ahn, Pan, et al., 2010; Ahn, Xie, et al., 2010; González & Echaveguren, 2012).

RESEARCH METHODOLOGY

The green-lean modeling approach was implemented on a construction case study of earthmoving operations explained in the next section of this paper. ExtendSim v8 (Diamond et al., 2010), a DES modeling software, was utilized to model the project operations. Required environmental data including fuel consumption of machineries and equivalent amount of carbon emission were obtained from online databases and linked to the DES model. As an example, depending on type and model, a loader consumes up to 0.4 liters diesel fuel per kilometer in normal conditions (asphalt road, standard road slope, standard traffic and so on) and emits up to 1.08 kg CO_2 eq. (Guidance for Voluntary Corporate Greenhouse Gas Reporting, 2011). The case study model has then been verified and validated based on real project data to ensure that the model both matches to the modeler's understanding of the system and the real project. If a model has been verified, validation seeks to determine whether the modeler truly understood the real system. This step was performed with the participation of project personnel who were familiar with the earthmoving operations. Several improvements based on both green and lean construction practices were then applied on the base (as-built) model in order to assess both production and environmental performance. Improvement models are explained in detail in further sections. 100 simulation runs were then developed for each experimental scenario to assure estimates with a 95% confidence interval and a relative error of less than 5% (Law, 2007). Low standard deviation of the variables proved that an average would be the most proper result for the simulation output analysis.

OVERALL SIMULATION FRAMEWORK

Foundation construction of three telecommunication masts (MTN-Irancell project in Mashhad, Iran, 2006) has been considered as the case study (foundation dimensions: 8m×8m×3m, excavation volume: 300m^3 = 10m×10m×3m). Project operations were modeled in ExtendSim with the aim of optimizing the environmental and production variables. Excavation process (P1) in the first site (S1), second site (S2) and third site (S3) include movement of trucks from the truck parking site to each of the sites (T Move), load of trucks by the loaders available onsite (L/T Excavate), hauling the excavated material to the dumping site (T Haul), the dumping operation (T Dump) and finally returning back to the truck parking site (T Return). While the P1 operations are finished at S1, S2 and S3, concrete pouring process (P2) starts with filling mixers at the batching (M Fill), followed by hauling the concrete to the sites (M Haul), dumping concrete to fill the excavated volume (M Dump) and returning back to the batching (M Return). Figure 1 shows a layout of the earthmoving operations in both P1 and P2 processes at all sites (S1, S2 and S3). T, L and M represent Truck, Loader and Mixer, respectively. These letters clarify what type of construction machineries are assigned to each of the operations.

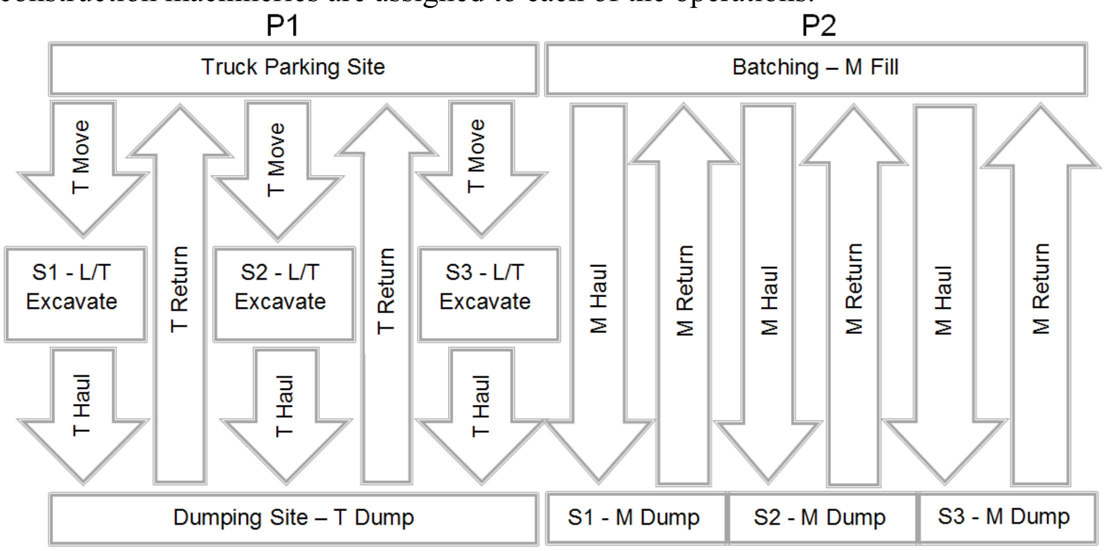


Figure 1: Layout of the Earthmoving Operations

Regarding the modeling purpose (assessing construction machineries' environmental and production performance), rebar processing has not been considered in this model. Input data such as duration of operations were obtained from project personnel who were closely familiar with the operations. As a result, triangular distributions were fitted to the duration data obtained from subjective information provided by project personnel.

Table 1 shows distance, duration, expected fuel consumption and carbon emission of the project operations.

Carbon emission is calculated based on fuel consumption and emission factor as follows.

- Carbon Emission (kg CO_2 eq.) = Fuel Cons. (lit) × Emission Factor (kg CO_2 eq./lit)

Emission factor is dependent upon different variables such as type of machinery, type of fuel and the way in which the fuel is combusted. Based on both project information and environmental data obtained from online databases, emission factor was considered 2.7 kg CO_2 eq./lit in this research (Guidance for Voluntary Corporate Greenhouse Gas Reporting, 2011). Depending on the nature of operations, fuel consumption of different types of machineries is calculated based on distance (movement of machineries from one place to another) or working time (duration of the operations).

- Fuel Cons. T1 (lit) = Working Time (hr) × Cons. per Time (lit/hr)
- Fuel Cons. T2 (lit) = Distance (km) × Cons. per Distance (lit/km)

Based on project cost data, hiring costs of machineries have been considered 10$/hr, 15$/hr and 25$/hr for truck, mixer and loader, respectively. The diesel fuel cost was also considered 0.8$/lit in this project. Depending on total process time of P1 and P2 at S1, S2 and S3; type of machineries; and the number of each type; fuel cost and hiring cost of machineries are calculated separately for each of the operations in the model. Consequently, the total cost is calculated by adding up the fuel cost and hiring cost of machineries.

- Total Hiring Cost ($) = Process Time (hr) × Hiring Cost per Time ($/hr) × No. of Machineries
- Total Fuel Cost ($) = Fuel Cons. (lit) × Fuel Cost per Volume ($/lit)
- Total Machineries Cost ($) = Total Hiring Cost ($) + Total Fuel Cost ($)

Table 1: Required Input Data for Building up the Base (As-Built) Model

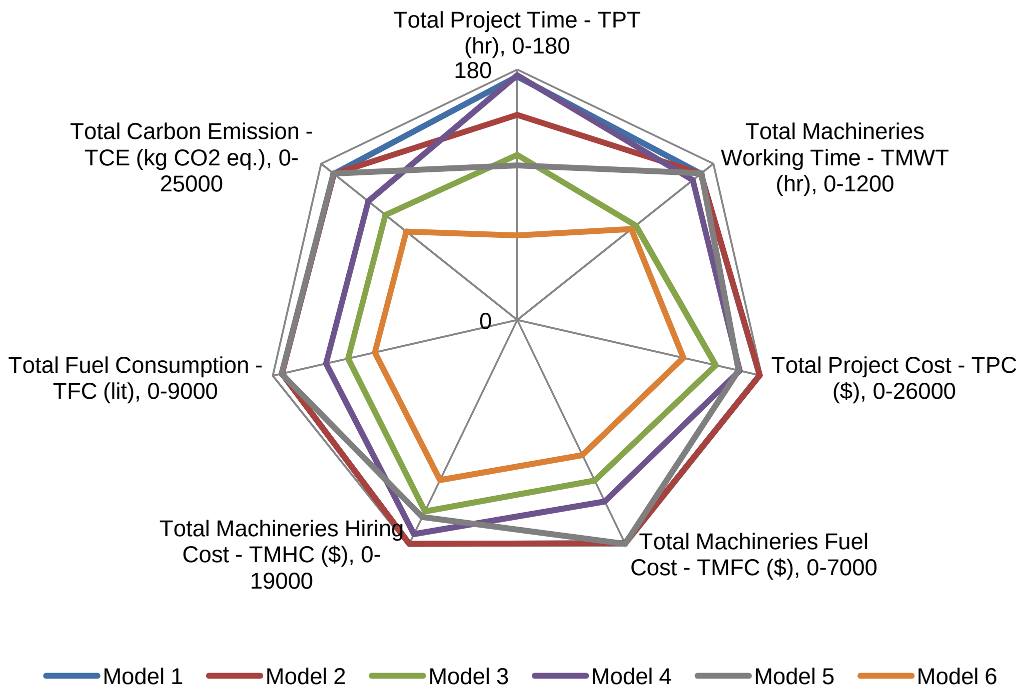
Activity	Distance (km)	Duration (min) Triangular Distribution			Expected Fuel Consumption		Expected CO_2 Emission	
		Min.	Max.	Mode	lit/km	lit/hr	kg/km	kg/hr
T Move	24	24	72	43	0.25	–	0.675	–
	13	13	39	23.5	0.25	–	0.675	–
	12	12	36	21	0.25	–	0.675	–
L/T Excavate	–	6	13	10	–	L: 9.5	–	L: 25.6
					–	T: 5	–	T: 13.5
T Haul	39	39	117	69.5	0.25	–	0.675	–
	14	14	42	25	0.25	–	0.675	–
	28	28	84	50	0.25	–	0.675	–
T Dump	–	1	3	2	–	5	–	13.5
T Return	14	14	43	26	0.25	–	0.675	–
M Fill	–	5	15	11.5	–	6	–	16.2
M Haul & M Return	4.5	4.5	13.5	8	0.3	–	0.81	–
	15	15	45	27	0.3	–	0.81	–
	10.5	10.5	31.5	19	0.3	–	0.81	–
M Dump	–	10	20	16.5	–	6	–	16.2

GREEN-LEAN IMPLEMENTATION

This section explains how green and lean construction practices were implemented to reduce both environmental and production waste in the project. Several experimental scenarios have been developed and applied on the base (as-built) model with the aim of improving the earthmoving operations. Removing non-value-adding activities or wastes from the earthmoving operations has been the main concern of building up the improvement models. The models enable the authors to demonstrate simultaneous assessment of environmental and production variables over time in the same simulation model. The analyses are based on the simulation outputs from the following six models: (1) Base (as-built) model of the project is considered as the first model. (2) Total project time of the second model is reduced by starting P2 immediately after P1 is finished in each of the sites, rather than starting P2 after P1 is completely finished in all sites. Reduction of the batch size (excavation volume) is the improvement approach implemented on the second model. In such a case, depending on the excavation volume and the process times, total project time is reduced by starting P2 before P1 is finished in each of the sites. (3) Reducing construction process waste in transportation is achieved in the third model by doubling the truck capacity. The hiring cost is also doubled with respective changes on duration of truck filling process, fuel cost, fuel consumption and carbon emission. The effect of double truck capacity on both environmental and production variables are discussed based on the results obtained from this model. (4) Similar to the third model, construction process waste in transportation is reduced in the fourth model through certain changes on truck routing. In this case, trucks return to the sites immediately after the dumping process is finished. The “T Move” operation is omitted and respective changes on distances and durations are applied. (5) Approximated optimization of number of machineries based on trial and error method forms the fifth model. Several models were tested to approximately optimize the number of trucks, loaders and mixers in order to reduce time and cost as production variables and fuel consumption and carbon emission as environmental variables. The number of trucks and mixers in each of the sites were increased from 3 and 2 to 5 and 3, respectively. The number of loaders remained constant (1 at all sites). (6) All the previous improvements were applied together into the sixth model to demonstrate the total potentiality on reducing environmental and production waste. Next section of this paper discusses the improvements achieved.

RESULT AND DISCUSSION

Figure 2 demonstrates the environmental and production variables in all the models based on total project time, total machineries working time, total project cost, total machineries fuel cost, total machineries hiring cost, total fuel consumption and total carbon emission (kg CO_2 eq.). This shows that improvements of the second model reduce the total project time by 27 hours (174-147), although it does not affect the total cost of machineries (including fuel cost and hiring cost). The improvements do not affect the environmental variables (energy consumption and carbon emission) as well. It also confirms that although improvements of the second model including reduction of the batch size (excavation volume) reduced the total project time, the improvements do not affect the total machineries working time. Based on the results of the third and fourth models, reducing construction process waste in transportation significantly affects both environmental and production variables. The third model saves 56 hours on total time (174-118), \$4669 on total cost (25773-21104), 2430 litters on total fuel consumption (8658-6228) and 6562 kg eq. on total CO_2 emission (23377-16815); while the fourth model does not affect the total project time but saves \$2109 on total cost (25773-23664), 1622 litters on total fuel consumption (8658-7036) and 4378 kg eq. on total CO_2 emission (23377-18999). In the third model, truck capacity and hiring cost both increased to double. Corresponding changes on duration of truck filling process, fuel cost, fuel consumption and carbon emission were also applied into the model. Significant results obtained from this model are illustrated in Figure 2. Although, the third model affects both environmental and production variables more than the fourth, time cost performance and reduction of energy consumption and carbon emission in the fourth model is quite considerable. In addition, the third and fourth models save 398 (1123-725) and 49 (1123-1074) hours on total machineries working time; \$1944 (6926-4982) and \$1297 (6926-5629) on total machineries fuel cost; and \$2724 (18846-16122) and \$812 (18846-18034) on total machineries hiring cost, respectively.



Model	TPT	TMWT	TPC	TMFC	TMHC	TFC	TCE
1	174	1123	25773	6926	18846	8658	23377
2	147	1123	25781	6926	18854	8658	23377
3	118	725	21104	4982	16122	6228	16815
4	175	1074	23664	5629	18034	7036	18999
5	111	1127	23533	6942	16590	8678	23432
6	60	698	17666	4190	13475	5238	14143

Figure 2 – Environmental and Production Variables (Models 1-6)

The results of the fifth model demonstrate that optimization of the number of machineries noticeably affects project time and hiring cost. However, working time and fuel cost of machineries have remained almost constant. It saves 63 hours on total project time (174-111) and $2240 on total cost of machineries (25773-23533). Results of the first and fifth models show almost the same fuel cost. Therefore, the savings on total project cost is only dependent upon the total hiring cost in this model. In addition, the fifth model shows that optimization of number of machineries does not considerably affect the environmental variables.

Based on the results of the sixth model, applying all the improvements together significantly reduces both environmental and production waste. In general, the principles applied to this construction case study, reduced total project time by 66% (1-60/174), total machineries working time by 38% (1-698/1123), total cost of machineries by 32% (1-17666/25773), total machineries fuel cost by 40% (1-4190/6926), total machineries hiring cost by 29% (1-13475/18846), total fuel consumption by 39% (1-5238/8658) and total CO_2 emission by 40% (1-14143/23377).

CONCLUSION AND FUTURE RESEARCH POTENTIAL

Waste reduction principles and techniques used in lean construction and green construction can be eventually understood as similar. However, as the focus of green and lean construction in waste reduction is different, this study proposed an integrated green-lean approach for simultaneous assessment of environmental and production waste in construction using DES modeling. The principles or techniques applied to the case study of this research could also be categorized as lean or green. As the focus of environmental analysis has mainly been on materials rather than the processes involved in production system, the scope of this research is limited to analyzing the processes. Based on the results obtained, the possibility and feasibility of the proposed approach was tested. The results not only support the great potential on reducing both environmental and production waste in construction, but also highlight the potential of using this approach for managing a broader concept of waste in construction, supported in simulation techniques. Applying such environmental analyses to different road construction operations, contributes to the development of more sustainable roading projects considering environmental aspects in the planning phase or even during the construction phase. The authors are developing a DES-based generic model capable of analyzing environmental impacts of road construction operations. Materials' inputs and outputs are expected to be added to the model. In such a case, the model is expected to be linked to Life Cycle Inventory (LCI) database to record associated environmental inputs and outputs; Life Cycle Impact Assessment (LCIA) database to evaluate associated impacts on environment; and Life Cycle Costing (LCC) data to consider imposed environmental costs. Besides, this research has the potential to propose a decision support tool in which environmental and production variables are simultaneously optimized by means of a multi-criteria decision-making approach able to prioritize variables based on weighting factors decision makers adopt. This paper is part of an on-going research.

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