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RESEARCH ARTICLE

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Proposing a "lean and green" framework for equipment cost analysis in construction

Abstract One limitation of previous productivity-driven research on equipment selection and operation simulation lies in the fact that the green aspects of construction activities have been largely neglected in analysis of cost-efficiency of construction operations. On the other hand, studies attempting to measure greenhouse gas emission due to construction activities have yet to develop a methodology that correlates their findings and implications with construction productivity. In order to address the immediate need for improving the sustainability performance of construction projects, it is imperative for the construction industry to evaluate greenhouse gas emission as a cost factor in construction planning, equipment selection, and cost estimating. In this context, this paper formalizes an integrative framework for equipment cost analysis based on the concepts of lean construction and green construction, aimed to guide the selection of appropriate construction equipment considering exhaust emission and productivity performance at the same time. The framework is elaborated in earthwork construction in order to evaluate the impact of greenhouse gas emission in estimating equipment hourly rates and assessing greenness and sustainability for alternative equipment options.

Keywords green construction, lean construction, equipment, simulation, earthwork construction, sustainability, productivity

1 Introduction

Modern construction relies on the use of heavy equipment for material handling and installation in field operations, turning engineering designs from virtual reality into physical reality. Hauling trucks, backhoe excavators, scrapers, graders, and rollers play the leading part in earthwork and road construction, while cranes and pumps are indispensable in high-rise buildings and industrial construction. Among major industries (including manufacturing, power, heavy chemical, and mining), the construction industry has made the highest amount of investment in machinery with an aim to deliver higher productivity and to save cost (Yoon et al., 2014). Supported by the Lean Construction principles, the high ownership cost of heavy equipment provides incentives for construction companies to utilize equipment at the highest efficiency practically possible. Like manufacturing, lean in construction also shares the same cocktail of basic ideas including scope definition for continuous improvement, less complex organizational structures, elimination of all possible waste (including idling) and efficient use of resources (Green, 1999). Here, variability in the flow of the construction process is considered to be the major impediment to optimizing the system performance. According to Koskela (1992), variability in the workflow considerably contributes to the extended process cycle time and cuts system throughput by increasing the amount of waste in the process. Therefore, operation cycle time has been chosen to be the key performance indicator of a construction process (Thomas et al., 2002). This operation cycle time is dependent on the operation efficiency of finite construction resources. Therefore, equipment use planning is crucial to meet the tight project deadline and budget and to improve productivity performances and profit margins. For instance, under special circumstances, to ensure the highest possible utilization of available resources, the use of major construction equipment had been planned to operate over a whole construction season without stopping for a single moment (Vision, 2017). At present, emerging Internet of Things (IoT) technologies enabled by state-of-the-art sensors and wireless communication technologies have led to research and develop-

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ment of solutions capable of tracking utilization, exact physical position, and operation statuses of equipment in the field in real time (Hasan and Lu, 2017). Equipment operating parameters tracked in real time include engine error codes, mileage, actual engine hours, temperature, vibration, time, location, and other similar metrics (Zhang et al., 2017). This potentially leads to an immediate reduction in total cost and engine downtime, thus significantly enhancing construction productivity and equipment utilization (Lu and Hasan, 2018).

The World Commission on Environment and Development (1986) defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. As a major contributor to the global economy, the construction industry is also among the largest consumers of natural resources and producers of pollutants (U.S. Environmental Protection Agency, 2009). There has been a growing concern on the negative impact the construction industry exerts upon environmental sustainability. The goal of implementing eco-friendly or green construction methods should be set forward during the planning phase to establish sustainable development practice (Yates, 2014). Eco-friendly construction equipment (particularly emitting less greenhouse gases) is prerequisite to implementing green construction. At present, heavy equipment used in the construction process produces long term negative environmental impact on soil, water, and air (Ahn et al., 2013); as the majority of equipment in operation is powered by internal combustible engines and fuelled by diesel (Rasdorf et al., 2010). On the other hand, the new generation of greener equipment with higher fuel economy and lesser carbon footprint is generally associated with much higher ownership cost than conventional equipment (Gransberg and O’Connor, 2015). Thus, it can be difficult to justify the implementation of greener equipment and further investment in development of green technology in the highly competitive construction industry driven by the need to improve the short-term bottom line. An immediate need is identified to develop an analytical framework to guide selection and use of heavy equipment in construction that would be not only lean (cost-effective, economically sustainable) but also green (environmentally conscious and sustainable).

This paper addresses the identified gap by formalizing such a framework based on the concepts of lean and green construction in support of planning equipment use and estimating equipment costs with environmental impact considered as an additional performance criterion. The framework is elaborated and illustrated in the application context of earthwork construction case through (1) the use of simulation for modelling a construction system and (2) quantifying equipment costs in regards to greenhouse gas emission and other environmental impacts.

2 Literature review

2.1 Lean aspect of construction

Application of modern management science coupled with proper use of engineering technology is identified as the catalyst to the advancement of the construction industry (Aziz and Hafez, 2013). Howell and Ballard (1998) mentioned that “implementing lean concept does not demand making construction to deliver standardized products, rather implementation starts by accepting the ideal of excellence offered by lean production for performance improvement in construction”. Lean construction is a “way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value”, (Koskela et al., 2002). Nonetheless, lean construction is not straight forward to implement due to the uniqueness of the final construction product (Tommelein, 1998; Salem et al., 2006).

One of the most popular applications of lean thinking in construction is the Last Planner System (LPS), which plans and schedules construction activities through improving flowability of the work rather than controlling workers (Ballard and Howell, 1994). LPS was proven to be effective in increasing planning efficiency, developing foresight, smoothing workflow variations, and removing uncertainties from construction processes (Fernandez-Solis et al., 2013). Conte (2002) discussed the practical feasibility of applying lean principles in construction and described a real-world case study in which the production time was 20% to 30% shorter, while at the same time the production cost was lowered by 5% to 12%. Based on lean construction principles, Miller et al. (2002) proposed the harmonization between main contractors and subcontractors as a prerequisite for better productivity; Thomas et al. (2002) proposed reducing variability to improve performance and improving labour work flow reliability. Lean construction practice can be integrated with the building information modelling (BIM) system to support project control mechanism (Sacks et al., 2010). In addition, modelling a construction process in the virtual environment and testing it through simulation was proven to be cost effective in ascertaining the applicability of the lean principle (Al-Sudairi et al., 1999; Mao and Zhang, 2008).

Traditionally, waste is only defined in the physical sense and represents an expected outcome of most processes in the construction industry (Tommelein and Li, 1999; Li and Wang, 2016). With the propagation of lean concepts, the definition of waste has been expanded in order to factor in other forms of waste elimination pertaining to the construction industry. The core of the lean philosophy is the elimination of any activity or material that does not provide value to the customer or add value to the delivered product (Ko and Chung, 2014). The application of "lean thinking" in the construction industry breaks down waste into six types (Shang and Sui, 2014), namely: (1) waste from overproduction, (2) waste from rejects, (3) waste from transportation, (4) waste from over-processing, (5) waste from materials, (6) waste from waiting.

2.2 Green aspect of construction

Many researchers have argued that a successful application of lean construction creates significant environmental improvement by being more resource and energy efficient (Dunlop and Smith, 2004; Farrar et al., 2004; Al-Sudairi, 2007; Mao and Zhang, 2008). Hence, many studies have focused on the relationship between lean and green, reaching the consensus that implementing practices that are both lean and green in construction would enhance environmental and production performances (Golzarpoor and Gonzalez, 2013). Although various lean and green approaches distinctly differ in regard to environmental and waste management on construction projects (Rosenbaum et al., 2012), they share the common goal of reducing unnecessary waste as much as practically possible. Environmental waste is generated from unnecessary use of resources as well as the release of substances into the habitat that could harm human health or the environment (Golzarpoor et al., 2017). For instance, the emission of CO_2 from construction machinery and excessive introduction of foreign soil largely account for the bulk of environmental waste as a result of heavy civil construction activities. To quantify the environmental impact of the construction industry, Kim et al. (2015) developed a project management system to forecast CO_2 emission based on construction schedules; CO_2 emission was measured during the construction phase of a building complex development using a life cycle inventory database.

In an attempt to address the immediate need for how to price the carbon cost so as to control greenhouse gas emission, it is imperative for the construction industry to evaluate CO_2 emission as a cost factor in construction planning, equipment selection, and cost estimating. In particular, heavy construction equipment is identified as a significant contributor to pollution (Lewis and Rasdorf, 2017). Therefore, it is crucial to improve methods to monitor, estimate and control the rate of emissions from construction equipment (Heidari and Marr, 2015; Barati and Shen, 2016). One of the control mechanisms is to ensure optimum selection and use of construction equipment, aimed at producing the minimum emission (Hummer et al., 2017; Carmichael et al., 2019).

2.3 Simulation for construction planning

To facilitate the implementation of lean and green construction, discrete event simulation was chosen to identify deficiencies in construction systems (Uriarte et al., 2015). The simulation of construction processes afforded an effective means to identify bottlenecks and evaluate measures to be taken for productivity improvement while eliminating the need to consume time and resources required for experimentation of different settings for executing tasks in the field (Moselhi and Alshibani, 2009). It is noteworthy that simulation has the ability to evaluate systems evolvement over time, where variables change at separate points in time or as causes of specific circumstances (Law, 2015). Hence, simulation has the capacity to model an engineering system composed of dynamic entities and complex relationships between production units and resources, thus lending the ideal tool to simultaneously assess environmental factors and production variables of a system (González and Echaveguren, 2012).

Research on equipment selection and operation simulation has been predominantly productivity driven, aiming to realize the objective of improving equipment utilization efficiency while delivering the project on schedule and under budget (AbouRizk and Hajjar, 1998). Shi (1999) applied neural networks to determine the number of haulers required for a particular excavator. Later, heuristic algorithmic innovations were integrated with simulation modeling so as to optimize earthmoving operations. Marzouk and Moselhi (2003) successfully established an automated system named Earth Moving Simulation Program, embedding heuristic algorithms into the simulation model to select a near-optimum fleet configuration. Cheng et al. (2005) proposed simulation optimization by combining genetic algorithms (GA) with CYCLONE simulation. Zhang et al. (2006) further proposed integration of particle swarm optimization (PSO) and construction simulation to determine the optimal resource combination. Optimization models for large-scale earthmoving operations were successfully developed utilizing GA, linear programming, and geographic information systems (GIS) in Moselhi and Alshibani (2009). Morley et al. (2013) applied discrete event simulation to optimize truck numbers by allowing for multiple truck and excavator types. One major limitation of previous productivity-driven research lies in the fact that the green aspect of construction has been largely neglected in the analysis of productivity and cost-efficiency of construction operations. A methodology based on the use of simulation for modelling a green-lean construction system in connection with quantifying equipment costs for greenhouse gas emission and other environmental impacts has not been formalized.

3 "Lean and green" framework

In formalizing a "lean and green" framework, the goal is set to select the leanest fleet in terms of avoiding over-production due to unbalanced production capacities between different types of equipment. The leanest fleet is conducive to eliminating equipment underutilization waste (such as idling and waiting) during construction, while delivering the highest production rate of the deployed fleet (UN/HR, i.e., the units of production completed by the crew in an hour). Next, given that particular fleet, the greenhouse gas (GHG) emission cost is defined as a function of the fuel consumption rate in addition to the hourly operational cost. The framework can be implemented for guiding equipment selection and evaluating available fleet alternatives, as shown in Fig. 1.

The basic principle of fleet balancing is to realize the full potential of a particular piece of equipment by delivering its productivity as high as practically possible. The equipment which is referred to as the leading resource governs the construction system. The provision of other supporting equipment is matched to the production rate of the leading equipment. To a limited extent, some over-capacity on the production rate of supporting equipment is generally allowed, so to lend a certain cushion ensuring the leading resource would operate at its full production capacity without experiencing unnecessary idling or waiting time. For instance, given the backhoe excavator governs the production, the number of trucks should be rounded up in balancing the production rate of trucks against the excavator (Peurifoy and Oberlender, 2013). All in all, redundancy in resource provisions needs to be removed; as such, a lean fleet that experiences the least amount of idling or waiting time is deployed during the construction process. Apart from tangible benefits with respect to productivity improvement, this also conforms to the Lean Construction philosophy in terms of avoiding over-production, reducing wastes, and striving for just-in-time services. Additionally, the leanest fleet lends the apparent advantage in cutting unnecessary greenhouse emission.

Lean construction essentially improves operation effi-

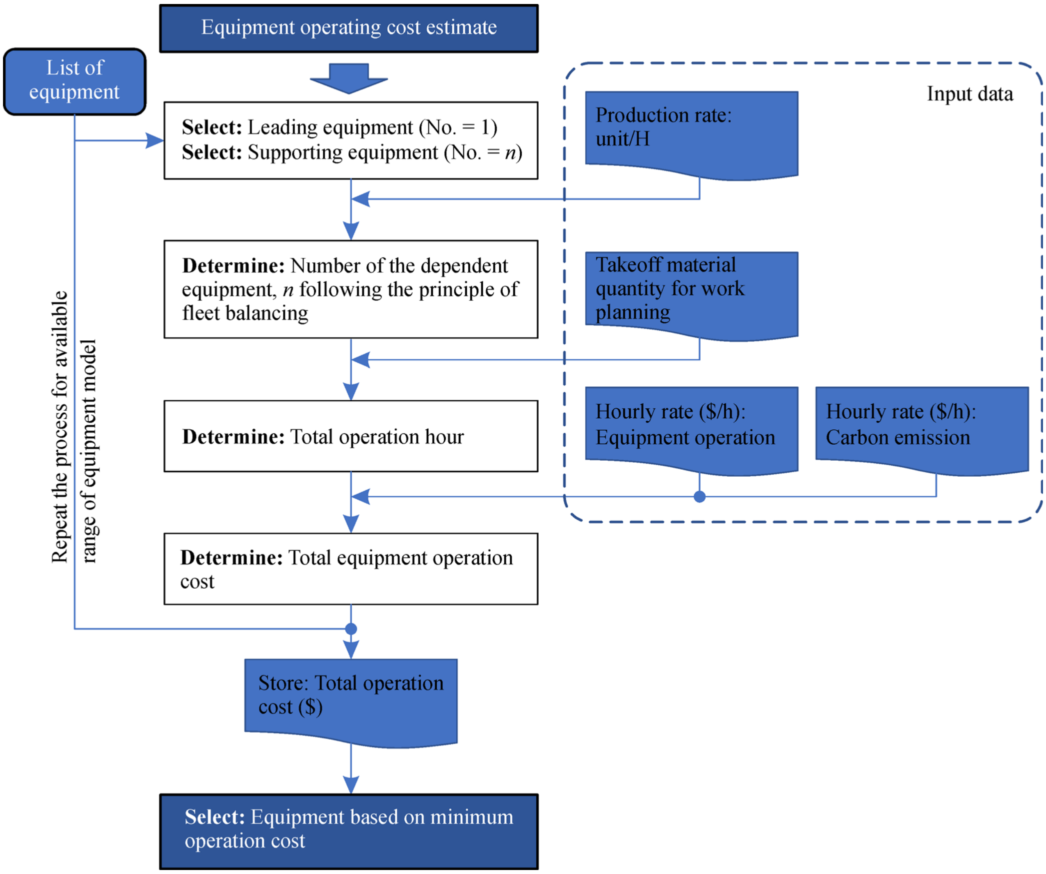

Fig. 1 "Lean and green" framework for equipment selection and cost analysis

ciency of a construction system by maximizing the utilization of equipment, labour and time, thus maximizing the generation of valuable output while minimizing the amount of wastes generated in the process. Nonetheless, green house emission is not explicitly considered as one type of waste or a performance indicator in the current scheme of lean construction. It is noteworthy that simulation modelling is adept at equipment selection and work planning by implementing the lean construction concepts (such as reduced waiting or idle time of resources and reduced inventory in process). The resulting leanest system is conducive to delivering higher operation efficiency, higher logistical efficiency, and improved productivity of the construction operation, but not necessarily leads to the attainment of high system performance measurements in connection with greenness and sustainability.

The “lean and green” framework being proposed extends both the lean concept and the simulation modelling technique by formalizing equipment cost analysis in consideration of environmental impact, more specifically, by quantifying the effect of CO_2 emission as a cost factor and devising an equipment hourly rate subject to environmental impact. Hence, the environmental waste is analytically represented in terms of the crew cost (hourly rate \$/HR) which is then applied to qualify the crew production rate (UN/HR) derived from simulation modelling based on lean construction principles. This ultimately results in a key performance indicator in terms of a unit cost (\$/UN), which unifies both “lean and green” aspects of construction activities and assists in comprehensive evaluation of alternative fleets in equipment selection and work planning. The ensuing case study illustrates the application of the proposed “lean and green” framework for minimizing equipment idling, mitigating environmental impact and analysing equipment costs in consideration of typical earthwork operations engaging excavators and hauling trucks.

4 Case study

The typical duo-equipment interactive process model in earthwork construction is illustrated in Fig. 2 with truck and excavator engaged in cyclic earthmoving operations. Note the flowchart model accounts for production unit flows with respect to truck (i.e., truck load) and excavator (i.e., bucket load), respectively. The number of bucket cycles *N* for loading one truck load is considered in the model. A brief description of the model is given considering specific equipment models: one CAT 336D excavator plus four CAT 735C trucks. 1.5 m^3 bucket for a CAT 336D excavator, 15 m^3 truck volume capacity for each CAT 735C truck; thus, it takes 10 ($N = 10$) buckets (loading cycles) to fill up one truckload. This is represented in the simulation model (Fig. 1) by defining the “10 + BLC” logical condition on Activity 10 “Load a truck”, prior to the start of Activity 4 “Travel on gravel (loaded)”; specifying “10 BL” ready for loading a truck at the end of Activity 8 “Travel on rough (empty)”. The take-off of the earthwork job results in 6900 m^3 of total cut volume, which is to be hauled over sections of gravel-surfaced haul road and rough ground haul road in the site. This quantity take-off is converted into the number of bucket loads (i.e., 4600) and the number of truck loads (i.e., 460) to be processed by the simulation model.

Figure 2 depicts the interactions between two separate resource-use processes in a typical material handling

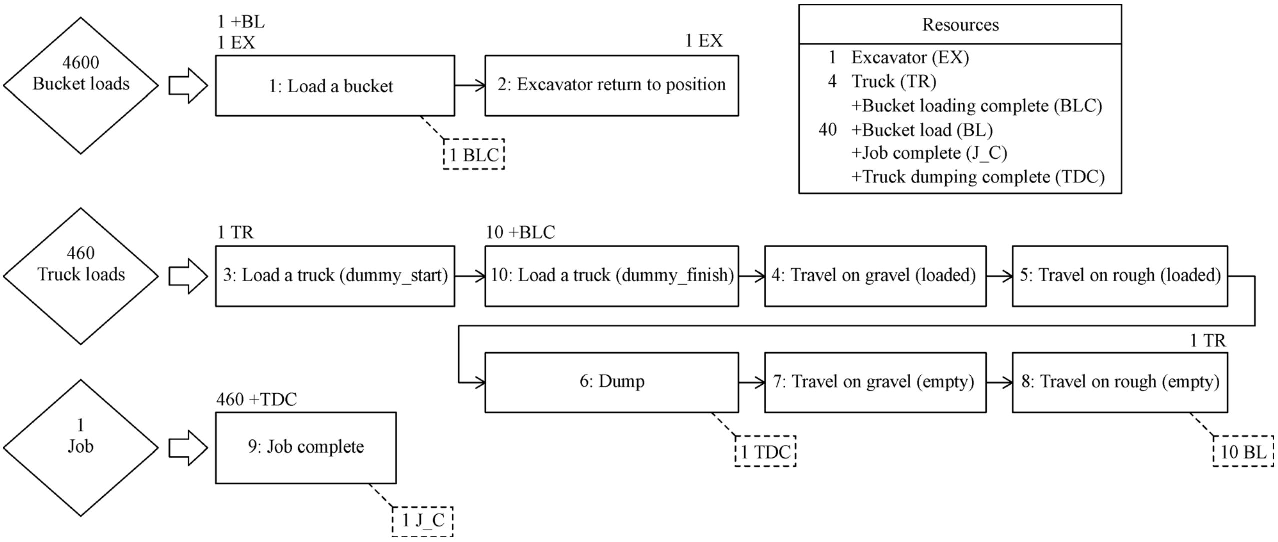

Fig. 2 Typical duo-equipment interactive process model in earthwork construction based on SDESA

system in construction (Truck vs. Excavator; which are engaged at the loading activity). Note the simulation model given in Fig. 2 is developed according to the process mapping protocol of SDESA; thus, it can be readily imported into the SDESA computer platform for discrete event simulation analysis. Note that SDESA represents the simplified discrete event simulation approach (SDESA) originally formalized by Lu (2003) in order to streamline the discrete event simulation modeling to resemble the experience of critical path scheduling while keeping essential functionalities and advanced features of simulation. SDESA distinguishes reusable resources and disposable resources. The reusable resource is used to model commonly seen crew resource such as labourers and equipment (for example “truck: TR” and “excavator: EX” in Fig. 2), while disposable resources are used to represent intermediate products or command units that are generated by one activity and required by another (such as “BL: Bucket Load” and “BLC: Bucket Loading Complete” in Fig. 1). Disposable resources can be used to effectively model the interdependent relationships among various activities or processes. SDESA provides the appropriate methodology to model and analyze such construction systems featuring dynamic resource engagement, resource transit and likely queuing events due to uncertainties inherent in activity times which are generally represented with statistical distributions. It is worth mentioning there is no need to write any computer code to execute the duo-equipment interactive process model established by applying SDESA. Interested readers can refer to Lu and Wong (2005) and Lu et al. (2008) for more details on modeling techniques, computer platform, and practical applications of SDESA.

The present research only takes advantage of the SDESA model to illustrate construction processes in the formulation of the proposed “green and lean” framework and the configuration of the leanest fleet of the earthwork construction production system. The focus is set on performing interactive simulation experiments to evaluate various “what-if” scenarios for fleet selection and productivity improvement. Simulation is instrumental in designing the “leanest” fleet and reducing equipment idling time due to production capacity mismatch between hauling and loading, e.g., fixing the fleet composition (i.e., how many CAT 735C trucks to rent in matching up with one CAT 336D excavator) and improving the crew production rate (i.e., how many cubic meters of earth to process over an hour). Based on evaluating relevant data sourced from Caterpillar Handbook (Caterpillar, 2017), we assessed truck hauling speeds, hauling distances on gravel road vs. rough ground for a number of earthmoving jobs; we also evaluated the excavator’s cycle time based on the “average” work condition in excavating. Running simulation experiments to evaluate various scenarios, the recommended number of CAT 735C trucks was found to be three on this job; which would best engage with one CAT 336D excavator, resulting in shorter job duration and lower crew cost. The following hourly rates for equipment were applied in calculating the direct cost of each job: the hourly rate for CAT 735C articulated truck plus driver was \$120/h; the hourly rate for CAT 336D hydraulic excavator plus operator was \$245/h.

It is noteworthy the hourly rate of deployed equipment (\$/h) which is used for calculating the direct construction cost can be sourced from industry-wide or company’s equipment cost databases. They only represent the conventional definition of equipment cost, which includes ownership cost (depreciation, interest expense, insurances, taxes etc.) and operating cost (fuel, lubricant, maintenance and repair, and operator etc.) In the proposed new framework, definition of the hourly rate denoting environmental impact is formalized by factoring in costs in connection with CO_2 emission and other environmental surcharges.

5 Environmental costs of operating equipment

5.1 Production rate for selected equipment

For a type material handling system engaging two types of equipment resources as shown in Fig. 1, the first step is to set the specific models for “Truck” and “Excavator”. Then, collect cycle time data for selected equipment in consideration of job conditions being analyzed; apply simulation modeling to identify the optimum configuration of the fleet and determine the optimum production rate of the fleet in terms of UN/HR according to the procedure commonly used to guide simulation experiments. For instance, Yi and Lu (2018) developed a methodology based on the use of a simulation model in analysis of planned haul jobs one at a time, identifying the best number of trucks and determining the best combination of trucks and excavators, given the excavator being the governing resource.

5.2 Parameters on engine fuel economy

The base fuel for construction equipment is selected as diesel. Then, the fuel economy in terms of gallon of diesel consumed per hour (Gal/h) can be obtained from equipment manufacturer’s manuals; note, such rates are generally calibrated at ideal work conditions and dependent on engine technology and horsepower. Given a particular equipment model, three most important factors that need to be considered in adjusting the fuel consumption rate to the actual job conditions are temperature, atmospheric pressure, and operating state of the engine (which is commonly defined by the operating factor).

Temperature and atmospheric pressure are commonly set in ideal laboratory conditions (such as temperature of 68°F or 20°C, air pressure of 1 Atmosphere or 101 kPa) in calibrating the fuel economy, and the actual data can be readily measured on a particular job in the field. Note, the operating factor is associated with job demand on the engine power (the percent of horsepower the engine delivers in the field), depending on actual physical conditions on the specific job (the hardness of the soil, the depth of the cut, the haul road surface and slope); plus time efficiency in construction planning and field management (e.g., equipment downtime — the equipment is not available; equipment idle time — equipment is available but idling its engine due to waiting to be processed or queuing in traffic). As per Peurifoy and Oberlender (2013), the operating factor is generally fixed as 60% as a rule of thumb in estimating fuel consumption cost for construction equipment. In the present research, how to determine the operating factor in a quantitative way considering operations simulation modeling along with enabling sensor technologies is elaborated in the subsequent section.

5.3 Equipment operating factor

The operating factor takes into account the combined effect of the engine demand factor and the time efficiency factor when operating equipment in construction. With enabling sensor technologies, it is practically feasible to monitor the engine's downtime precisely in real time. Engine downtime means the engine is switched off for maintenance and repair (hence unavailable for use in construction). The engine uptime is further divided into engine working time vs. engine idling time. With effective simulation methods for job planning and emerging sensor technology for engine monitoring, it has become practically feasible to obtain reliable, time-stamped data on the status of utilization and demand of the engine for particular equipment during construction, so to calculate engine uptime for different working states (including idling), plus engine downtime. Herein, it is assumed engine data has been collected on trucks and excavators involved in simulation; the calculation of equipment operating factor is demonstrated as follows.

For the truck, in one hour, the engine downtime is 10 min associated with the engine power demand at 0%. Out of the remaining 50 min engine uptime, 10 min is recorded as loading time, with the average engine power demand at 30%; 15 min hauling on gravel road with the average engine power demand at 50%; 20 min hauling on rough ground haul road with the average engine power demand at 70%; 5 min is recorded as dumping time, with the average engine power demand at 50%. The operating factor is calculated through Eq. (1) where P_e is the % engine power demand, t_a is the time required to complete an activity in the cycle, and t_op is the truck operation time including all the components. Hence, the operating factor is averaged to be 0.4 for a truck as calculated below:

$$f = \frac{\Sigma P_\mathrm{e} \times t_\mathrm{a}}{t_\mathrm{op}}, \tag{1}$$

$$f_\mathrm{trk} = \frac{(10 \times 0 + 10 \times 0.3 + 15 \times 0.5 + 20 \times 0.7 + 5 \times 0.5)\ \mathrm{min}}{60\ \mathrm{min}} = 0.4.$$

For the excavator, the time duration and average engine demand percentage are collected for idle (10 min, 10%), excavating (20 min, 90%), swing full (10 min, 70%), swing empty (10 min, 50%), loading truck (10 min, 60%). No downtime occurs to the excavator. The operating factor is averaged to be 0.62 and is calculated as per Eq. (1) as shown below.

$$f_\mathrm{exv} = \frac{(10 \times 0.1 + 20 \times 0.9 + 10 \times 0.7 + 10 \times 0.5 + 10 \times 0.6)\ \mathrm{min}}{60\ \mathrm{min}} = 0.62.$$

5.4 Equipment hourly rate considering environmental impact

Given operating factors determined for equipment involved under specific job conditions, the fuel economy rate, $R_\mathrm{fe(adjusted)}$ (Gal/h), is first adjusted by multiplying the normal rate, $R_\mathrm{fe(normal)}$ (Gal/h), with temperature coefficient (f_temp), pressure coefficient (f_press), and operating factor, $f_\mathrm{equipment}$, as in Eq. (2).

$$R_\mathrm{fe(adjusted)} = R_\mathrm{fe(normal)} \times f_\mathrm{temp} \times f_\mathrm{press} \times f_\mathrm{equipment}, \tag{2}$$

f_temp, and f_press are in general greater than 1.0 when the equipment operates in field conditions. Further research will be needed to apply sensor technology and take measurements of temperature and air pressure, so as to collect such data along with the engine performance data for deriving the actual fuel economy data in the field. Thus, sophisticated mathematical models or predictive analytics models can be established to embellish the basic equation as in Eq. (2). Last, the equipment hourly rate due to consuming fuel is calculated as Eq. (3).

$$R_\mathrm{env(\$/h)} = R_\mathrm{fe(adjusted,\ gal/h)} \times C_\mathrm{fuel(CO_2(kg)/gal)} \times C_\mathrm{e.i(\$/CO_2(kg))}. \tag{3}$$

Note, $C_{\text{fuel}(\text{CO}_2(\text{kg})/\text{gal})}$ is a constant for a particular type of fuel. For example, according to EPA greenhouse gas calculator (U.S. Environmental Protection Agency, 2009), C_{fuel} is 8.887 $\text{CO}_2(\text{kg})/\text{gal}$ for gasoline and 10.22 $\text{CO}_2(\text{kg})/\text{gal}$ for diesel. Note the base fuel is selected as diesel in this case, for other types of fuel, such as gasoline, electricity, or a hybrid engine technology the equivalent C_{fuel} needs to be separately determined.

It is noteworthy $C_{\text{e.i}(\$/\text{CO}_2(\text{kg}))}$ is a case-dependent decision variable. How to set this coefficient can be determined through a “trial and error” process by evaluating various alternative scenarios. In addition to environmental impact, the social cost needs to be factored in as well. For instance, for an older model truck, the hourly rate is \$50/h; by adding the environmental surcharge, the total hourly rate nearly doubles due to less fuel efficiency of the engine technology, say, the total hourly rate would be \$100/h. In contrast, the hourly rate for a newer model truck can be \$70/h due to higher ownership cost, which is 40% higher than the older model. Against the older model, obviously, the newer model is not the appealing choice with regards to the contractor’s bottom line. By contrast, factoring in the fact that the new engine technology delivers higher fuel economy thus leading to substantially lower carbon footprint, the total hourly rate considering environmental impact for the newer model truck is determined as \$90/h. Thus, the hourly rate with environmental impact considered would lend considerable cost advantages to the new-generation, greener equipment, thereby facilitating its acceptance and utilization in the construction industry. Another example is to add \$50/h environmental surcharge to the truck hourly rate when it is used to handle a job that moves borrowed material to fill a particular area in grading an environmentally sensitive site.

6 Demonstration on equipment environmental cost calculation

A CAT 772G dump truck has a fuel consumption rate of 2.41 gal/h while a CAT 770G dump truck has a fuel consumption rate of 2.66 gal/h (Caterpillar, 2017). Even though the 770G model is older, due to its lower load capacity and shorter time to be loaded and to dump, it has an operating factor of 0.55 while the CAT 772G has an operating factor of 0.46. If both trucks are considered on an identical job in the same site, we can assume the identical temperature coefficient and pressure coefficient of 1.3. Hence, their respective fuel economy rate is equivalent to 1.87 gal/h and 2.47 gal/h as calculated below,

$$R_{\text{fe(adjusted}-\text{CAT 770G)}} = 2.66\,\text{gal/h} \times 1.3 \times 1.3 \times 0.55$$

$$= 2.47\,\text{gal/h},$$

$$R_{\text{fe(adjusted}-\text{CAT 772G)}} = 2.41\,\text{gal/h} \times 1.3 \times 1.3 \times 0.46$$

$$= 1.87\,\text{gal/h}.$$

Since both use diesel as the energy source, is applicable to each case a $C_{\text{fuel}(\text{CO}_2(\text{kg})/\text{gal})}$ of 10.22 $\text{CO}_2(\text{kg})/\text{gal}$; and for demonstration, $C_{\text{e.i}(\$/\text{CO}_2(\text{kg}))}$ of \$0.41/kg is set as the unit cost for environmental impact due to CO_2 emission based on referencing the case study presented in Wang et al. (2017). It is herein emphasized that $C_{\text{e.i}(\$/\text{CO}_2(\text{kg}))}$ is not a constant but a decision variable subject to corporate and government policies. How to quantitatively evaluate this decision variable based on alternative social and environmental agendas can be a further research subject. The hourly rate for environmental cost given a CAT 772G truck and a CAT 770G truck is \$7.84/h and \$10.35/h respectively, as calculated below,

$$R_{\text{env}(\$/\text{h})-\text{CAT770G}} = 2.47\,\text{gal/h} \times 10.22\,\text{kg}(\text{CO}_2(\text{kg})/\text{gal})$$

$$\times \$0.41/\text{kg} = \$10.35/\text{h},$$

$$R_{\text{env}(\$/\text{h})-\text{CAT772G}} = 1.87\,\text{gal/h} \times 10.22\,\text{kg}(\text{CO}_2(\text{kg})/\text{gal})$$

$$\times \$0.41/\text{kg} = \$7.84/\text{h}.$$

In short, CAT 772G eclipses CAT770G in terms of having a lower hourly rate for environmental impact (CO_2 emission). Therefore, despite a higher operating factor and a lower conventional cost rate, the older model with a higher environmental cost rate is more expensive to operate than a newer greener model in this case.

7 Conclusions

As a major contributor to the global economy, the construction industry is among the largest consumers of natural resources and the main producers of pollutants. There has been a growing concern on the negative impact the construction industry exerts upon environmental sustainability. In particular, heavy equipment use in the construction process produces considerable pollution. At present, the majority of equipment being utilized is powered by internal combustible engines and fueled by diesel, potentially generating long term negative environmental impact on soil, water, and air. The new generation of greener equipment with higher fuel economy and lesser carbon footprint is generally associated with much higher ownership costs than conventional equipment. Thus, it can be difficult to justify the implementation of greener equipment in the highly competitive construction industry that is driven by the need to improve the short-term bottom line. To a certain extent, this may hamper further development of green technology in connection with construction equipment in the near future.

There is a lack of an analytical framework to guide selection and use of heavy equipment in construction that would be not only lean (cost-effective, economically competitive) but also green (environmentally conscious and sustainable). This paper has addressed the identified gap by formalizing such a framework based on the concepts of "lean and green" in construction engineering and management. The proposed framework is instrumental in designing a "lean and green" fleet simply by analytically assessing the production rate (UN/HR) and the environmental impact hourly rate ($/HR) in a systematic fashion. In short, the framework would be conducive to (1) lending quantitative decision support to plan "lean and green" equipment use in construction — instead of guessing or googling — and assist the contractor in estimating unit costs of heavy equipment use in bidding construction jobs and (2) planning a cost-effective, environmentally conscious process to utilize heavy equipment with higher efficiency and execute more environmentally sustainable construction operations.

Further research will be needed to apply sensor technology to take measurements of temperature and air pressure, collect such data along with equipment engine performance data and actual fuel economy data in the field. Then, sophisticated mathematical models or predictive analytics models can be established to embellish the basic equation as given in Eq. (1). With continuous technological advances into the near future, we expect more automation and higher efficiency in operating construction equipment through innovations, which would result in leaner, more productive, safer ("operator-less") fleet and lead to further improvement on construction productivity; at the meantime, it would be equally critical to make construction equipment greener by significantly improving fuel economy, utilizing new energy to power heavy equipment, while substantially reducing greenhouse emission. It is also hoped the concept of equipment hourly rate with respect to environmental impact as proposed in this paper would lay the groundwork for future research in respect to green construction.

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