Carbon emission evaluation of heavy equipment on dam construction site using discrete event simulation

Chunna Liu¹⁴, Qiong Wu², Wenzhe Tang³ and Yi Liu³

¹China Institute of Water Resources and Hydropower Research, China 100038; ²CITIC Construction Co., Ltd. Beijing, China 100027; ³State key Laboratory of Hydroscience and Engineering in Tsinghua University, Beijing, China 100084

⁴Email: liucn@mail.tsinghua.edu.cn

Abstract. The construction industry is considered to be one of the largest contributors to greenhouse gas (GHG) emissions globally, accounting for around one-third of the total in the world. Carbon emissions generated from heavy equipment on dam construction site are normally estimated without distinguishing the working modes, which may not represent on-site situations. Thus, this paper aims to evaluate carbon emissions of heavy equipment on dam construction sites, by establishing a methodology and applying the Discrete Event Simulation (DES) model. The case study demonstrates that DES model is validated to simulate the working models accurately, and the idling time of heavy equipment can influence carbon emissions a lot. It is suggested that dam project stakeholders should develop appropriate equipment management plans by using DES and improve the working efficiency, realizing the carbon reduction.

1. Introduction

Global warming causes a great concern throughout the world, and the carbon emission increment is the main factor. According to the statistical data [1], the construction industry is a major source, taking up about 20% of global energy consumption, has generated around one-third of the global carbon emissions [2]. The energy consumption of the building construction sector consists of approximately 9% of the total one in China [3]. Hence, we should take the construction processes, during which emissions occur intensively, more seriously [4,5], especially for dam projects [6]. The life cycle of a dam project contains the phases of material production, transportation, construction, operation and demolition. Among which, the energy consumption comprises probably 12% and the carbon emissions generated take up to approximately 8% during the construction stage [7].

In China, the government and its associated administrative entities aim to promote savings in carbon emissions in the construction stage through relevant legislations, and encourage the contractors to follow the requirement of carbon reduction [8]. Thus, project contractors face the challenge of meeting the emerging requirements to reduce the environmental impacts during construction processes [9]. In this stage, many researchers have investigated carbon emissions generated from the heavy equipment, which account for around 40% of the total in different dam projects [6]. There is a clear opportunity to reduce carbon emissions from construction processes through better on-site heavy equipment management [10,11].
Regarding to the engine data of heavy machine in NONROAD, the 15% of on-site time is in idling [12]. The emissions from operational modes of heavy equipment are higher than those in idling modes [13,14]. However, because there is a lack of awareness about identifying carbon emissions from different equipment working modes [15], the operational efficiency that indicates the efficient use by reducing the idling time is often overlooked [16]. Thus, how to evaluate carbon emissions generated from heavy equipment in different working modes, and improve the efficiency play an important for project contractors to realize the target of carbon reduction. Based on the aforementioned, this paper aims to evaluate carbon emissions generated from heavy equipment on dam construction sites, in order to allow project stakeholders to make a better plan to improve the on-site equipment efficiency, reducing carbon emissions during construction processes.

2. Methodology

In the previous study, Ahn and Lee utilized Discrete-Event Simulation (DES) to evaluate the emission performance of construction operations in earthmoving operations [16]; they defined the operation efficiency as the total operation time divided by the valuable operating time and formulated the environmental impacts generated by each resource as a function of the operational efficiency. González and Echaveguren integrated DES method into the research framework to study the incorporation of environmental goals in the design of a road construction operation [17]. The DES model can be applicable to other types of projects that do not have historical data. Such an approach allows project stakeholders to compare planning alternatives of construction operations and to find a better way to reduce carbon emissions. Thus, in this paper, DES model is developed to simulate different equipment working modes during dam construction processes and estimate carbon emission without many historic data.

2.1 Discrete-event simulation (DES) in dam construction

A construction simulation model can represent the construction processes, thus can be used to develop appropriate project management plans [18]. A DES model is developed based on Stroboscope platform [19]. Stroboscope concludes activity cycle diagrams and employs the three-phase activity-scanning paradigm. ‘It is therefore naturally adept for complex systems where many resources collaborate to carry out tasks as is typical in construction’ [20]. Construction processes of dam projects heavily rely on the use of energy-intensive construction equipment, such as excavators, cranes, vibrators, and bulldozers etc. Such usage of construction equipment is greatly influenced by planning and control decisions of project managers. Thus, a DES model is established through focusing on the equipment usage. The simulation model consists of a series of activities including different pieces of equipment used for each activity. The model also has detailed information about the equipment (e.g. type, emission rate, and operation efficiency), which is critical to generate different carbon emissions.

2.2 Carbon emission evaluation

Carbon emissions generated from heavy equipment are closely related to the working modes [15]. Accordingly, the authors formulated the carbon emission (E) as follows

\[
E = \sum_{t=\text{equipment}} T_{\text{value}} \times (\alpha \times EF_{\text{operating}} + (1 - \alpha) \times EF_{\text{idling}})
\]

where \( T_{\text{value}} \) means the total working time. \( \alpha \) represents the equipment efficiency (i.e. the ratio of valuable operating time to total working time) of each piece of equipment, which is provided by the developed DES model. \( EF_{\text{operating}} \) is defined as the emission factor (tCO₂/h) for the operating modes and \( EF_{\text{idling}} \) is the emission factor (tCO₂/h) for the idling modes.

\[
EF_{\text{operating}} = \sum C_e \times EF_{\text{electricity}} + C_o \times EF_{\text{oil}}
\]

where \( C_e \) and \( C_o \) are the estimated fuel and electricity consumption rate for each equipment item per hour respectively when equipment operating, which can be looked up in the Hydraulic Construction Mechanical Quota [21]. Either electricity or oil is used by each type of equipment. \( EF_{\text{electricity}} \) is the
emission factor of local electricity in Chinese Reference Life Cycle Database (CLCD) and $EF_{oi}$ is the emission coefficient for diesels, which is from BP China [22].

$$EF_{\text{idling}} = \beta \cdot EF_{\text{operating}}$$  (3)

In terms of $\beta$, based on the study presented by Lewis et al. [14], for each piece of equipment on site, the generalized ratio of idle to non-idle fuel use rates, as well as the ratio of idle to non-idle CO$_2$ emission rates, which are generally approximately 0.2 [13], since there is a linear relationship between CO$_2$ emission generation and diesel fuel consumption [23].

2.3 Case study of selected dam project

The selected dam project is located in western area of China. The conventional concrete technology is used on site and the construction process is shown in Figure 1.

![Case study of selected dam project](image)

2.3.1 Case study of selected dam project

The selected dam project is located in western area of China. The conventional concrete technology is used on site and the construction process is shown in Figure 1.

Based on the construction process shown in Figure 1, trucks, cranes, vibrators and bulldozers are chosen to represent the heavy equipment. DES model is established in Stroboscope software shown in Figure 2. The circles represent the types and the numbers of the resources. The rectangles represent the activities of on-site heavy equipment, and the rectangles lack of an angle represent the activities which need obtain resources. The numbers in the arrows mean the amount of resources obtained each time. Then on-site videos were recorded for different equipment activities respectively, and each activity was repeated no less than 25 times. Then we got the monitoring time distribution of each equipment activity shown in Table 1. The critical values of chi squared and K-S tests for 25 samples were 7.81 and 0.264 respectively. According to the data in Table 1, every distribution result was less than these values and passed the examination of Chi Squared and K-S.

![Figure 1. Dam construction processes](image)

| Event activity       | Time distribution | Chi Squared | K-S   |
|----------------------|-------------------|-------------|-------|
| Truck loading        | Uniform(22,31)    | 1.08        | 0.2   |
| Truck transporting   | Exponential(60)   | 3.32        | 0.229 |
| Truck unloading      | Uniform(21,28)    | 1.72        | 0.234 |
| Crane loading        | Uniform(10,35)    | 0.44        | 0.16  |
| Crane transporting   | Normal(49.12,4.6) | 2.04        | 0.196 |
| Safety inspection    | Exponential(34.36)| 0.76        | 0.139 |
| Crane unloading      | Exponential(13.04)| 1.4         | 0.24  |
| Crane returning      | Normal(48.76,3.93)| 2.36        | 0.177 |
| Bulldozer working    | Normal(45.88,5.45)| 1.08        | 0.126 |
| Vibrator working     | Normal(21,8,4.68) | 3.32        | 0.197 |
| Vibrating moving     | Exponential(8.16) | 5.24        | 0.139 |
| Manual vibration     | Exponential(16.44)| 0.256       |       |
| Manual movement      | Uniform(2,5)      | 0.76        | 0.24  |

Then authors further input the operating time of each equipment activity into the DES model, and set the resource amounts applied on construction site.
3. Simulation results

Once inputting the operating time of each equipment activity into the DES model and set the resource amounts applied to the construction site, we ran the DES model until 146718m³ concrete poured.

3.1. Simulation model output

The DES simulation results from Stroboscope platform are shown in Figure 3. The resources applied in the model are calculated in the above column, and in the following column, working time of each on-site equipment activity can be seen clearly.

![Figure 3. Simulation results obtained from DES model.](image)

3.2. Model validation

Through analyzing the outputs of the DES model, the working time of different equipment activity can be used to validate the model [18]. Because the energy consumption rate of cranes is highest among all...
of the equipment [21], authors applied crane activities as an example. The average monitoring time of different activities is compared with the outputs of the DES model. The results are shown in Table 2.

**Table 2.** Comparison of the average working time of crane different activities.

| Activities | Monitoring results (Second) | DES model results (Second) | Difference |
|------------|------------------------------|----------------------------|------------|
| Loading    | 21.92                        | 22.52                      | 2.27%      |
| Transporting | 48.71                       | 49.12                      | 0.84%      |
| Unloading  | 12.83                        | 12.89                      | 0.47%      |
| Returning  | 48.87                        | 48.75                      | 0.24%      |
| Idling     | 75.30                        | 76.47                      | 1.55%      |

It can be seen that DES methodology could accurately simulate the operation duration of crane activities. The simulation results are less than 2.3% differences from the on-site monitoring ones. Regarding to the idling time, there are only about 1.55% differences. Similarly, the comparisons of the average working time of bulldozer, trucks, vibrators are calculated as well. The differences between monitoring results and DES model output of these equipment are less than 2%. It is validated that the DES model is reliable to represent the working modes of the heavy equipment and calculate carbon emissions.

### 3.3. Carbon emission results

According to the carbon emission calculation equations (1) to (3), the electricity consumption rate of crane is 266 kW·h, and the carbon emission rate of electricity is 0.91 kg CO₂/kwh. The estimated carbon emissions generated from heavy equipment of different working time results are calculated in Table 3.

**Table 3.** Carbon emission comparison of different working time results.

| Amount        | Monitoring results | DES model results | Differences |
|---------------|--------------------|-------------------|-------------|
| CO₂ emission  | 247.7kg            | 249.7 kg          | 0%          |
| Differences   | 0%                 | 0.8%              |             |

Carbon emissions from monitoring results are set as the basic scenario. The comparison results showed that, the difference is only 0.8%.

### 3.4. Methodology analysis

Life Cycle Assessment (LCA) has gained the importance as an objective method to evaluate the environmental impact of construction practices [24]. The methodology applies the total working time as the operating time to calculated carbon emissions. Hence, the evaluation results obtained from on-site monitoring and LCA methodology were compared in Table 4.

**Table 4.** Carbon emission comparison of different working time results.

| Amount        | Monitoring results | LCA results |
|---------------|--------------------|-------------|
| CO₂ emission  | 247.7kg            | 348.9 kg    |
| Differences   | 0%                 | 40.9%       |

It can be seen that if we used the LCA methodology without distinguishing the operating or idling time of the heavy equipment, the difference would reach to 40.9%. When the working time lasts much longer, for example 1 month or 1 year, it would be really time consuming to get the monitoring time of different working modes of heavy equipment. Therefore, it is reliable and necessary to establish DES model to calculate carbon emissions during the construction processes.
4. Discussion for improving the working efficiency

Controlling working efficiency of on-site equipment would be the major factor (possibly the only factor) for construction contractors to reduce carbon emission during construction process, since all the quantity of materials used in building dams have already been determined in the design stage. Valuable working time of each type of equipment is a fixed value when there is a designed working load. The changeable value is the non-valuable working time, in other words, the idling time [16]. Reducing the idle time of construction equipment on site not only helps reduce the fuel use and construction-related emissions, but it also helps extend the life of engine, providing safer work environment for operators and workers on site [25]. Thus, in this study, we demonstrated the benefit of applying DES model to calculate carbon emissions of heavy equipment on dam construction sites by identifying the idling time. When the contractors make plans at the beginning stage of construction, they could establish the construction procedures in DES model, by inputting resources and monitoring time distribution of each activity. They are encouraged to compare the idling time of equipment and estimate carbon emissions of different construction options in the planning stage, trying to take effective measures to improve the working efficiency, resulting in carbon reduction. Then the request of relevant legislations in carbon emissions reduction could be satisfied to some extent.

5. Conclusions

Based on the above study, it can be demonstrated that the DES methodology could correctly represent the dam construction processes, and the idling time of heavy equipment can influence the carbon emission performance significantly. Compared with LCA methodology, which is difficult to distinguish the working modes of heavy equipment, carbon emissions can be calculated more accurately by using DES model, without too much overestimation. Therefore, this study contributes to encourage stakeholders in making better plans to reduce the idling time and improve the working efficiency, realizing the carbon reduction.

On the other hand, there are some limitations inherited from the selection of carbon emission rates of idling. Also, the carbon emission rates for working and idle modes were determined by some representative data, rather than equipment-specific data. In the future, it is necessary to build a database of fuel and electricity use of different equipment, and emission rates that can be expandable to construction equipment commonly used with various engine sizes.

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