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DEVELOPMENT OF SIMULATION MODEL FOR ESTIMATING GAS EMISSIONS FROM EQUIPMENT IN RAILWAY CONSTRUCTION PROCESSES

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ABSTRACT: The railway construction utilizes several pieces of heavy equipment resulting in exhaust emissions such as pollution and greenhouse gas emissions (GHG). The release of emissions can affect the environment and human health. Although many previous studies have attempted to approximately estimate the amount of emissions, they did not consider the detailed processes of construction. The simulation model can be applied to improve this limitation and provides the ability to allocate resources and optimize the construction process. In addition, it can help to analyze alternative approaches to reduce emissions. This paper presents the development of simulation model to analyze the amount of exhaust emissions from the equipment usage in railway construction. It compares the amount of exhaust emissions from the situation in the railway construction process, which will demonstrate the effects on the relationship between the amount of exhaust emissions and the construction approach. As a result, this research provides an alternative method to manage exhaust emissions from the railway construction process and resource management.

Keywords: Gas Emissions, Railway Construction Processes, Equipment, Simulation Model

1. INTRODUCTION

At the present, gas emissions (e.g. GHG, pollution) have been found as a critical concern in infrastructure construction because it has a wide impact on environmental issues on earth such as global warming and respiratory problems. The impact of gas emissions has been summarized in Table 1. One cause of the emissions is the equipment operation from infrastructure construction projects. Recently, the issue of GHG emissions in infrastructure projects has been given much attention because the amount of GHG emissions has a strong effect on climate change [1].

Table 1 The effect of gas emissions [2]

Gas	Impact
CO_2	CO_2 is a component of greenhouse gasses that affect global warming
HC	HC can form ozone, which makes the body more vulnerable to infection
CO	CO is a toxic gas; it can form smog and causes respiratory problems
NO_x	NO_x can generate smog, ozone, and acid rain. It causes respiratory problems
PM	Aggravates asthma and other respiratory problems, such as coughing

Due to the economic growth of the ASEAN region, the railway construction project is found as the bedrock of infrastructure in Thailand. The railway network has been planned to build more than 3,000 kilometers of double track. Generally, the ballast track is selected as the standard railway in Thailand. The structure of ballast track consists of the track bed and track panel. Firstly, the track bed has three main layers, which are the subgrade, sub-ballast and ballast. The construction of the track bed is composed of several processes, which are the moving, grading and compacting of materials. Secondly, the track panel is comprised of sleepers, rails, and fastenings. The processes of the track panel consist of the track panel installing, ballast tamping, leveling, and surfacing [3]. As the ballast track construction consists of many processes, it is required to use heavy diesel equipment (truck, excavator, grader, compactor, rail-loader, tamper, regulator, and stabilizer etc.) to complete the work tasks. Based on the amount of future railway construction in Thailand and the high equipment utilization, the railway construction could contribute to the GHG emissions. Therefore, it is essential to quantify emissions in detail for the construction process. This information could help to manage GHG emissions.

Currently, many research studies have attempted to quantify emissions in railway construction. First, Chang and Kendall (2011) estimated construction related GHG emissions of the high-speed rail (HSR) project through a process-based life cycle assessment (LCA) [4]. Based on LCA analysis, the emissions of the HSR track bed was estimated from three main components, which are the material production, material transportation, and equipment. It was found that the level of equipment utilization has an influence on the emissions in track bed maintenance, and the unpredictable factor of emissions during construction is the amount of time to finish the task. Second, Krezo et al. (2016) studied greenhouse gas emission from railway plain-line renewals which are calculated from the emissions embodied approach [5]. It evaluated CO_2 emissions from fuel consumed by all machines and embodied energy emissions of materials required per meter. From the above discussion, the result in a life cycle emission assessment associated with the construction project has a degree of uncertainty. It could be crude and imprecise. Previous research studies have focused on the environmental life cycle analysis, which has some uncertainty about the unpredictability of construction time, a limitation in the estimated fuel consumption and difficulty to manage emissions.

Furthermore, a few studies have focused on the railway construction processes. For this reason, the author wanted to develop the model for estimating emissions in railway construction. After that, the model will be used to manage and find the emissions minimizing approach. In this paper, an emission estimation model will be developed for the track bed operation, which will focus on the subgrade layer construction of 1 kilometer.

2. LITERATURE REVIEW

Currently, the method of estimating gas emissions in the construction work is diverse, which can be summarized from the literature review into four methods.

2.1 Emissions inventory model

The emission inventory model aims to identify the emission factor and load factor for estimating emissions of off-road construction equipment. The Environmental Protection Agency (EPA) proposed the NONROAD model for estimating the emission factor in different types and models of heavy equipment [6]. Based on this model, the emission factor for each type of equipment is calculated by using the equation that uses parameters from tables such as type, model year and horsepower range of the equipment. The equation and tables can be found in document EPA-420-R-10-018 [6]. The result of the analysis shows the emission factor for CO_2, CO, NO_X, HC, SO_x and Particulate Matter (PM) of each type of construction equipment. From the NONROAD model, the emission factor is the average emission rate, which can be used for calculating emissions from the equipment operation. In addition, the NONROAD model provides the general load factor in three different stages, which are idle, partial load and transient operating conditions. Each operating condition has a relationship with the equipment group; for example, the backhoe is categorized as a transient operating condition. Thus, the load factor of the backhoe group uses the load factor from a transient condition.

Based on the NONROAD model, there are some limitations of estimating emissions. First, the calculation of emissions does not specify a specific equipment model. Second, the NONROAD model typically gives emissions per year. Therefore, it may not be precise enough for calculating emissions in specific work cycles.

2.2 Lewis's model

Lewis's model was developed for identifying the CO_2 emission factor for off-road construction equipment. The emission factor from Lewis's model is determined from the CO_2 exhaust emission rate. The model is based on gathered emissions from the real condition of the equipment operation using the portable emission measurement system (PEMS). The model can determine the emission factor from different parameters such as the activity of the equipment, engine power, model year, and engine tier [7]. Thus, this model can help to identify the emission factor from a variety of engine powers and engine tiers. Later, Lewis's model extended their research to quantify the emissions of equipment during idle time by using the general ratio of idle to non-idle fuel usage rates [8]. Therefore, the use of the emission factor from Lewis's model can give a specific value of emissions that depends on the equipment model and its activity. However, the number of equipment models and engines are limited due to ongoing research. Some equipment is unavailable for railway construction such as roller tiers and vibrating compactors.

2.3 Life cycle assessment

The life cycle assessment (LCA) is a technique for gathering inputs and outputs related to products and assessing their impact on the environment. It focuses on the CO_2 emission throughout the project life cycle such as planning, construction, operation, maintenance, demolition and recycling [4, 9, 10]. This method is used to evaluate the GHG emissions from fuel consumption and energy-related material production. First, GHG emissions from material production are estimated by multiplying the embodied emission factor with a quantity of materials. Second, the emissions from the fuel consumption of the equipment are estimated by multiplying the amount of fuel used with the emission conversation factor. The estimation of CO_2 emissions from fuel consumption is focused on the equipment operation at the project level rather than specific equipment operation at the activity level.

2.4 Discrete event simulation

Discrete event simulation (DES) can be applied to simulate the work operation and estimate the emissions from fuel consumption. The application of DES in estimating emissions gives several benefits such as getting reliable statistical results on the equipment activity. It can be used to compare construction emissions from other scenarios and to aid the designing of the construction operation which has few emissions [11]. In addition, DES can simulate a project or operation by running chronologically occurring events [2]. As a result, the use of DES can give the benefit of emission calculation.

3. RESEARCH GAPS

From the discussion of above methods, the individual model of estimating emissions has some limitations. First, the LCA model is suitable for estimating the emissions throughout the project life cycle but it does not provide detail information about the process that releases more emissions. Second, the NONROAD model is used to estimate the emissions from equipment utilization and fuel consumption. The emission estimation is based on the utilization time of the equipment and emission factor. However, the emission factor is defined by the group of equipment rather than the specific type of equipment. Last, the Lewis model is used to overcome the limitation of the NONROAD model by improving the detail of emission factor. But the Lewis model has some limitations on the equipment types that could be applied.

Based on the limitation, the model to estimate gas emissions in railway construction is proposed by integrating the DES with the load factor, emission factor, and ratio of idle and non-idle CO_2 exhaust emission rates. Firstly, the DES technique is applied to building a construction simulation of the railway process. Secondly, the load factor is applied by using the power proportion in the operating conditions of each machine. Thirdly, the emission factor in our model refers to NONROAD. Lastly, the calculation of emissions uses the general ratio between idle and non-idle emissions from Lewis. The details of the model development will be described in the next section.

Although previous research studies have been applied, the simulation model for estimating the emissions of earthwork in road construction projects, there are some different characteristics between earthwork from road construction and track bed construction. Firstly, the cross-section of the track bed is different from the earthwork in the road construction project. Secondly, the types and models of construction equipment are different from road construction. Lastly, the study of emissions in the railway construction focused on the project life cycle rather than the process level. There is no research study on the emissions of railway construction at the process level. Therefore, it is necessary to explore the emissions of railway construction in each process. This information could help construction operators to minimize the emissions from the process viewpoint.

4. RESEARCH METHODOLOGY

Basically, the estimation of emissions requires basic information about equipment horsepower, operation time, load factor and emission factor. To estimate the emissions from railway construction, this research was designed into three main parts. The first part is related to preparing basic information for estimating emissions such as the conceptual model, activity information, equipment information, equipment operation time, load factor, and emission factors. The second part is about the development of the discrete simulation model (DES) by integrating it with the basic information. The third part is about the analysis of emissions from DES and validation of the model. The methodology for developing the emission model of track bed construction is shown as a flow chart in Figure 1. The details of the research method are described in the following section.

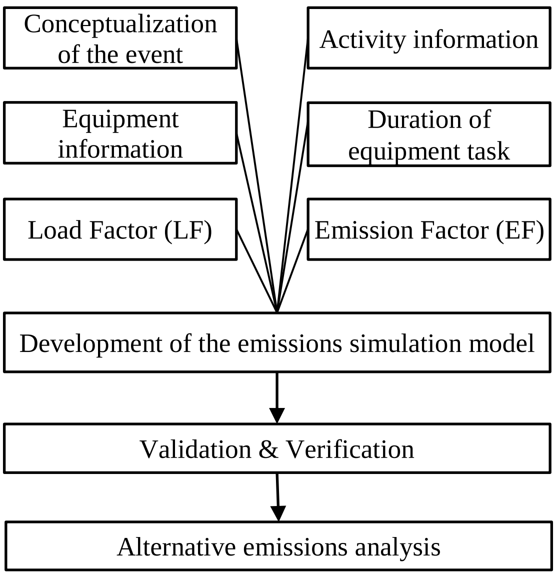

Fig.1 Methodology for developing the emission model of track bed construction

4.1 Preparation of basic information

The preparation of the basic information consists of the conceptual model, activity information, equipment information, equipment operation time, load factor, and emission factors. First, the conceptual model aims to illustrate the understanding of the railway construction process. The model consists of the activity and relationship in each railway construction operation. This model is generated from data through site observation and interviews. Then the model was drawn into a workflow diagram. Second, the activity information was used to support the activity simulation such as quantity and distance of railway construction. This information is gathered from the drawing and specification. Third, the equipment information was used to support the estimation of equipment emissions such as the capacity, speed, quantity, distance, and work conditions. This information was gathered from the equipment manual, interviews, and site observations. Fourth, the duration of the equipment task is one of the important data for the construction process modeling. Task duration can be a deterministic or stochastic value. The stochastic value can be fitted with statistical distribution from the observational sampling. To select the appropriate type of distribution, the goodness of fit was tested by employing Kolmogorov-Smirnov (K-S) and Chi-Squared test. Fifth, the load factor was the fraction of equipment power. It can be determined by observing and interviewing machine operators about engine acceleration and the percent of time spent on various equipment operating conditions. Moreover, these data are used to calculate the operating factor in the model, which can be found by multiplying the time factor (operating efficiency) with the load factor (operating power) [12]. Last, the emission factor is the average emission rate of a given exhaust emission, which includes CO_2, CO, NO_X, HC, SO_x, and PM. They were applied in the emission estimation model. These emission factors can be calculated by using the equation in NONROAD.

4.2 Development model for estimating emissions

In this section, the development of the simulation model for estimating emissions from railway construction operation is described. The main objective of the model development is to estimate the amount of emissions from the railway construction processes. The model development was created from the Simphony.NET program. Development of the model for estimating emissions uses the concept of discrete event simulation. This model development incorporates the DES tool with the parameters from the basic information that is mentioned in the section.

The conceptual modeling process is created by DES relation. The relationship starts with the creation of an entity (*e.g. truck, soil, distance*) or system component in the simulation system. Then entities arrive at the activity task (*e.g. loading, dumping, grading*) in the model. The resource (*e.g. excavator, truck, and grader*) will serve the entity, which is displayed as busy or available. If the resource is busy, the entities will wait for resource serving. In addition, the activity can take a certain duration of the task (*deterministic*) or random (*stochastic*). During every activity, there are events (*e.g. loading complete*). When the event starts and ends, the system state will be updated.

The emission estimate model was developed by making a diagram of the event occurrence created in the Simphony.NET. There are basic tools for creating a model such as *modeling elements, entities, directional arrows, and containers to hold information*. First, we created a model that represents the construction process using *modeling elements*. Each element describes a specific task, waiting for entities, and statistical collects (*e.g. compact, grading*). After that, the elements are connected together with *directional arrows*, and they form a representation of a railway construction process cycle. Next, the *container information* of the element can be defined to capture data during the process simulation such as production, a volume of soil, amount of emissions, etc. After creating a model, its data needs to be input for modeling. This consists of 1) entity information in *Create element,* 2) activity duration in *Task element,* 3) equipment or server information in *Resource element, and* 4) load factor, an emission factor of working and idling in *Resource element*. In order to model function as a real construction process, it is necessary to enter the working conditions such as quantity of soil, equipment capacity, distance, and speed. Furthermore, the element can be added to the formula (*Visual Basic*) in *modeling element* for terminate simulation and trace progress. For example, the simulation terminates when compaction activity is finished.

4.3 Analysis of the emission model and validation of the results

After modeling, it is necessary to verify the correctness of the model implementation and validate the model to guarantee the accuracy and credibility of the output. For this research, the emissions from the model cannot be directly validated with the actual measurement of emission, so it is essential to validate the process and productivity output instead for reflecting the accuracy and reliability of the model. The output of process and productivity will be validated to ensure the accuracy and reliability of the model.

Model verification consists of three steps including logical flow, debugging, and graphical connections. Firstly, the logical flow is verified by modeling the concept and logic of the model for sequential events using the proper model elements and links using the directional arrows. Secondly, debugging is used for verification and precaution of logic elements, coding and some system errors. Finally, graphical connections in Simphony.NET program can verify by tracing information such as event, time, and entities.

Model validation consists of 2 parts including an exploration of the model behavior and model outputs compared with outputs from the field. The validation is tested by comparing model outputs with the field data of hauling, grading and compacting productivity. This step looks for the chance of actual field data difference from model outputs by accepting a maximum error level of 5% [13]. In addition, the output data are normally (or approximately normally) distributed, which can be used to construct the confidence intervals around the mean. The simulation experiment was repeated several times. The run times of simulation were repeated by using the confidence intervals from the mean and variance of the results. This model required predicting the exact result at 95% confidence intervals. Initially, the simulation model takes 30 runs times.

Development of models to estimate gas emissions used the concept of discrete event simulation. It can increase the reliability of estimates such as operation hour, utilization rate, waiting time and length of the queue in each equipment. In addition, resource in the model can be adjusted to simulate the operation under the different task, the stochastic of event and duration. These scenarios will differentiate the amount of gas emissions. As the result, this simulation of emission model can be useful for managing equipment operation that released emission in railway construction.

5. RESULT

This section demonstrates the development of the emission estimation model for railway subgrade operation in trackbed construction. It showed a methodology for integrating the application of DES with the information from the emission estimate inventory model.

5.1 Characteristic of case study

This research was conducted at Single Rail Transfer Operator Project (SRTO) at Laem Chabang Port, Thailand. The distances of the main line are 5.9 km. The structure is ballast track, which consists of subgrade, sub-ballast, ballast, and track panel. Due to the limitation of the page, the case study focused on the subgrade operation of railway trackbed construction. In the subgrade section, it was required to fill 2,938 loose cubic meters of soil and the stockpile was located between 2 and 4 km away from the construction site.

To simulate the gas emissions per kilometer, this research collected representative data from 200 to 300 m of the construction operation. During the construction operation, there were three main processes including earthmoving, soil grading and soil compaction. The construction equipment consisted of the excavator, truck, grader, water truck, tier roller and vibrating roller. In addition, the site had a haul road for hauling materials.

5.2 Duration of task and attributes of equipment

According to the methodology, the duration of the equipment task was performed by site observation. It used the statistic tool to specify type of data distribution, which was verified by a goodness of fit test. The results of the analysis are presented in Table 2 and the duration task was used as the input to the simulation model in the later stage.

The attributes of the equipment are the important data for the simulation model. This research collected the attributes of equipment from the construction site. Based on the field data collection, the attributes of the equipment are described. Firstly, the capacity of the truck is equal to 8 m3 per dump. The speeds of the truck ranged between 14-16 km/hr under hauling conditions and 22-27 km/hr under return conditions. Secondly, the effective blade of the grader is equal to 3.2 m. Lastly, the effective width of the roller is equal to 2.13 m. This information will be used to calculate the quantity of work that can be produced by the equipment.

Table 2 Estimated duration of equipment task

Task	Distribution (minute)
Loading	Triangular (1.47,1.88,1.63)
Hauling	Normal (8.17,0.27)
Dumping	Constant (0.93)
Return	Normal (4.96,0.29)
Spread piles	Normal (5.59,0.22)
Mixing	Gumbel (4.54,0.27)
Grading	Normal (4.37,0.13)
Spay water	Constant (1)
Compaction	Gumbel (4.30,0.16)
Surface	Triangular (2.39,6.15,3.67)

5.3 Emission factor for construction equipment

The emission factor of all construction equipment was calculated by using the method suggested in NONROAD. The general idle to the non-idle CO_2 emission rate of equipment refer to Lewis's database. These parameters are calculated and reported in Table 3. In general equipment, the ratio of idle to non-idle CO_2 emission rate equal to 0.2, except for the ratio of the excavator which is equal to 0.3 [8]. After that, these data were applied in the emission estimation model of Simphony.NET program.

Table 3 Emission factors of construction equipment

Equipment	Emission Factors (kg/hr)				
	CO_2	HC	CO	NO_x	PM
Excavator	76.83	0.05	0.22	0.81	0.08
Truck	137.77	0.10	0.41	1.50	0.22
Grader	100.65	0.08	0.23	1.02	0.07
Water Truck	127.17	0.09	0.39	1.53	0.26
Vibrating Roller	81.07	0.06	0.23	0.85	0.08
Tire roller	71.53	0.05	0.21	0.75	0.08

5.4 Development of railway subgrade conceptual modeling

Based on the equipment process and workflow in the railway subgrade construction, the conceptual modeling of subgrade construction was illustrated by DES modeling. It showed the relationship of elements such as entity, resource, activity, event, and state. The conceptual model starts from the earthmoving process to the grading and compacting process. The truck entity starts from loading, hauling, dumping and return as cycle process. After dumping until the target, the grader was executed in the spreading, mixing, grading tasks and the compactor conducted subsequently. The sequence of events occurred in the chronological orders and links between elements as illustrated in Figure 2.

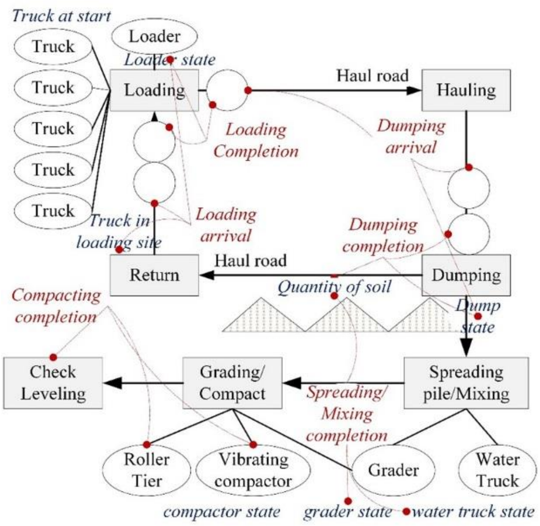

Fig.2 The conceptual modeling of subgrade construction

5.5 Development of DES model for estimating emissions in subgrade operation

In this paper, the DES model was used for the development of emission estimation in the subgrade operation by using the Simphony.NET program. It is a proper tool for modeling by advancing the time in the discrete segment based on important events. The conceptual model was created in the Simphony.NET interface by sets of model elements and directional arrows as shown in Figure 3. The basic information from the previous section were used as input data in the *modeling element*; for example, in the number of entities (5 *trucks*) and the emission factor (*working and idling*). In addition, several conditions of process were created by inputting supplementary information as shown in Table 2. For instance, the total dumping soil of 367 dumps, or 2,938 $m^{3,}$ were inputted in the *ConditionBranch* element for terminate simulation. The distance of hauling materials started from 2,000 m and increased around 2.7 m for every dumping. Based on this information, the emissions were calculated and captured from the resource *(equipment)* utilization that represents in *resource element* and generated the statistic of emissions. Moreover, the other modeling output data was generated as well.

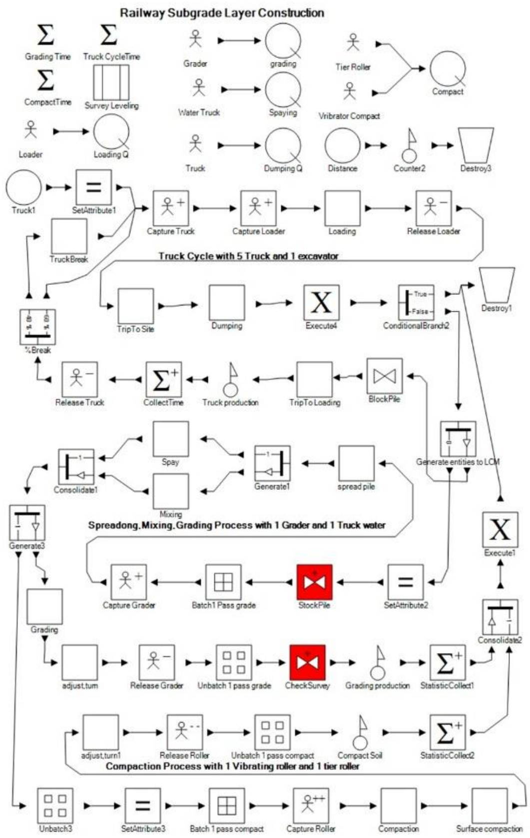

Fig.3 The railway subgrade layer construction model

5.6 Validation of the result

Based on the methodology, this section needs to confirm the correct implementation of the model and guarantee the accuracy of the output. The average productivity from the subgrade emission model was compared with the average productivity of filed data by student T-test accepting at error 5% (Type I). The sample data from the replicated model consisted of 50 run times. The validation of the simulation model is summarized in Table 4. As a result, the model is adequate in the prediction of average production. In addition, the result showed that the confidence interval time of hauling is 31.28 ± 1.35 minute per cycle while the confidence interval time of grading is 286.83 ± 48.9 minute per station at every 200 m. Last, the confidence internal time of compact is 16.79 ± 0.11 minute per trip.

Table 4 Validation of emissions estimation model

Activity	Model (m^3/day)		Field data (m^3/day)	T-test (5%,50)
	Mean	SD		
Hauling	541.44	46.08	547	Valid
Grading	485.28	23.52	479	Valid
Compact	477.60	22.56	479	Valid

5.7 Results

The results from the 50 run-time simulations at 95% confidence interval with 8 hours a day of work are shown in Table 5. The railway subgrade construction was completed within 6 days per km. and the emissions of CO_2, CO, HC, NO_X, and PM were produced by construction equipment. The amount of CO_2 emissions were found as the highest level of emissions which release 34,784.10 kg per kilometer of track bed construction. The highest level of CO_2 emissions mainly derives from five trucks (23,489.48 kg), two compactors (6,107.27 kg), a grader (4,762.39 kg), an excavator (1,689.66 kg), and a water truck (1,566.26 kg).

Table 5 The result of emissions base on railway trackbed construction

Type	Emissions (kg) in subgrade 1 km.				
	CO_2 (*10^3)	CO	HC	NO_x	PM
Excavator	1.69	2.28	0.56	8.26	0.86
Truck	20.65	50.92	11.98	183.88	26.96
Grader	4.76	10.63	3.64	47.56	3.36
Vibrating Compact	3.24	14.61	2.03	31.74	2.93
Tier Roller	2.86	7.88	1.80	28.36	2.93
Water Truck	1.56	1.11	0.26	4.08	0.59
Total	34.78	87.45	20.26	303.89	37.62

6. DISCUSSION

The result may lead to an analysis of the appropriate method for alternate emissions in construction operations such as resource management, construction methods, decrease of idle time, improved efficiency of construction, and operator training. This approach can be input to the model for simulation and experimental design for alternative results of emissions. The findings indicate that trucks had the highest emissions and demonstrated the need to change the number of the trucks (the origin of the truck is 5, hauling is 2,000 m) as shown in Figure 4. It shows the relationships between carbon productivity (production per ton of CO_2 emission) and performance productivity. When adding truck hauling, productivity is increased, whereas carbon productivity) is decreased, so it depends on the decision to manage emissions and performance.

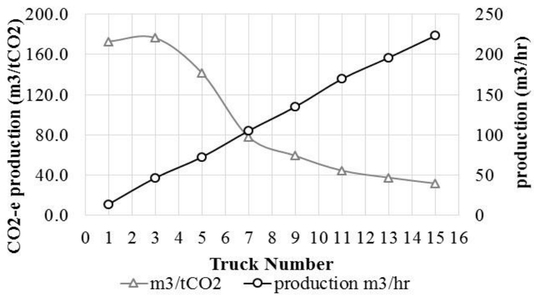

Fig. 4 the relation between CO_2 emissions and hauling performance

7. CONCLUSIONS

This paper presented the simulation model for estimating emissions of railway track construction which is composed of three main processes: earthmoving, grading and compacting. The DES approach is proved to be an alternative approach for estimating the utilization of the equipment. This model can estimate the duration and productivity that reflects the real process more than the historical data. The simulation model also helps to estimate the emissions in a reliable statistic. The model can support the decision-making on reducing emissions via productivity improvement of heavy equipment.

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