Optimization of Heavy Equipment Usage for Railway Track Works

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Abstract. Effective use of heavy equipment is an essential factor in construction work completion. Analysis of heavy equipment usage optimization for excavation work on the detour track construction of the Solo-Semarang Phase I double track project is intended to provide an overview of the number of needs, equipment combination, and time needed for maximizing the usage. Excavation work analysis was carried out in two work zones (Zone 1 and Zone 2) with a heavy equipment usage combination involving an excavator and dump truck. The method used in this study is a quantitative method through direct observation in the field and literature study. Based on the analysis result, the excavation work for each zone 1 and 2 need one excavator and five dump truck to optimize heavy equipment usage. In addition, the analysis resulted in a heavy equipment usage combination based on a match factor of 0,883 in zone 1 and 0,822 in zone 2 for excavation work with 13 and 10 work days.

Keywords: Heavy equipment · match factor · productivity · cycle time

1 Introduction

The Semarang-Solo double track work project was built as part of the 2030 national railway master plan (RIPNAS). [1] Rail traffic on the line can not be disrupted during construction. In order to deal with it, a temporary track (detour track) is constructed. One of the detours tracks is located on the double track project of solo Semarang 1st phase from Solo Balapan to Kadipiro with 1, 25 km length. The construction of the detour track is the same as an ordinary railway track which consists of an upper structure (rails, fastenings, and sleeper) and a lower structure (ballast, sub-ballast, and subgrade). [2] In order to the results of construction work to be adequately achieved, it is necessary to pay attention to the implementation time and other influencing factors such as the use of experts, tools, and materials [3].

Heavy equipment usage in detour track work is mostly used in substructure work, such as excavation work, embankment, soil improvement, sub-ballast laying, ballast laying, and compaction. Considering the excavation work duration is longer compared to other sub-structure construction, and the operating costs of heavy equipment are high, this study focused on analyzing the optimization of heavy equipment usage only on excavation work.

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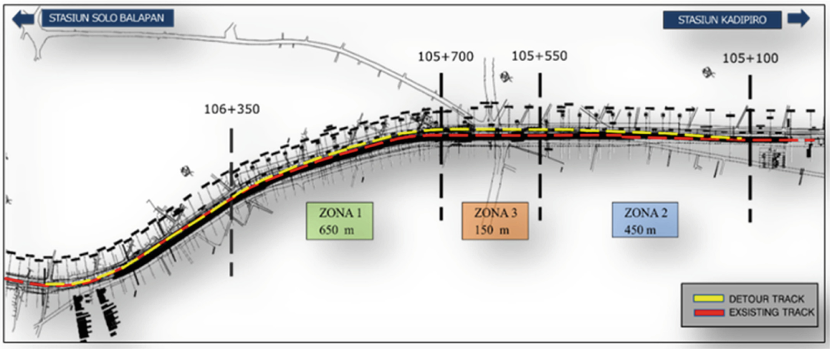

Fig. 1. Detour Track Layout

Table 1. Actual Heavy Equipment Recapitulation on Excavation and Embankment Work.

Work	Volume (m3)	Heavy Equipment	Type	Unit
Excavation (Zone 1)	3489,75	Excavator	Komatsu PC 78	1
		Dump Truck	Mitsubishi HD 125 PS	3
Excavation (Zone 2)	923,75	Excavator	Sany PC 135	1
		Dump Truck	Mitsubishi HD 125 PS	3

Heavy equipment is a critical factor in construction work because it makes humans do their job easier and results in the realization that their work can be done optimally [4, 5] (Fig. 1).

Based on the results of observations on the excavation work of the detour track, it has only been carried out in two work zones (zone 1 and zone 2) by using heavy equipment, specifically excavators and dump trucks. The use of excavators is 1 unit for each zone, and the use of dump trucks is three units for each zone. More details can be seen in Table 1. Based on the description above, the purpose of this research is to provide an alternative combination of heavy equipment in earthworks for more optimal work.

2 Method

The method used in this study is quantitative. The research started with field observations and literature studies to find parameters for the analysis of heavy equipment productivity, including the volume of work, type and capacity of heavy equipment used, duration of operation of heavy equipment, and work time and operating costs of heavy equipment. Based on the results of direct observations and literature studies, an analysis will be carried out, including the productivity of heavy equipment, actual combination, duration of work, and work compatibility (match factor), as well as a heavy equipment operating costs.

The equation for calculating excavator productivity uses the following Eq. 1 [3, 4, 6]:

$$Q = \frac{q \times 60 \times E}{Cm} \tag{1}$$

where:
Q = Production per hour (m^3/jam);
q = Production per cycle (m^3);
E = Work Efficiency.

To get production of a cycle excavator [3, 4, 6]:

$$q = q^{'} \times k \tag{2}$$

where:
q' = bucket head capacity and refer to equipment specification;
k = bucket head factor depends on type of soil.
The cycle time of an excavator can be calculated by Eq. 3 below [3, 4, 6]:

$$Cm = T1 + (2 \times T2) + T3 \tag{3}$$

where:
T1 = Digging Time (sec);
T2 = Rotating Time (sec);
T3 = Disposal Time (sec).

Dump Truck productivity can be calculated by Eq. 4 below [3, 4, 6]:

$$Q = \frac{q \times 60 \times E}{Cm} \tag{4}$$

where:
Q = Dump Truck Productivity (m^3/jam);
C = capacity (m^3);
Cm = cycle time (min);
E = equipment efficiency.

Dump Truck productivity can be calculated by Eq. 4 below [3, 4, 6]:

$$n = \frac{C \times K}{q'} \tag{5}$$

where:
n = Number of cycles to fill in dump truck;
q' = Bucket Capacity (m^3);
K = Bucket Factor.

Dump Truck cyclic time can be determined by the equation below [3, 4, 6]:

$$Cm = n \times Cms + \frac{D}{v1} + \frac{D}{v2} + t1 + t2 \tag{6}$$

where:
n = Number of cycles to fill in dump truck;
Cms = Cycle Time Loader (minute);
D = Distance (m);
V1 = Speed Average when Loaded (m/min);
V2 = Speed Average Empty Truck (m/min);
t1 = Time to Disposal + stand by time (min);
t2 = Time to loading and starting to loading (min).

The match factor is analyzed to get the working compatibility of a tool that works in series (interdependent) where there is no waiting time between each tool which results in less than optimal work. To calculate the match factor value, the following Eq. 7 is used [4, 7–10]:

$$MF = \frac{Na \times n \times Cms}{Nm \times Cmt} \tag{7}$$

where:
MF = Match Factor;
Na = Truck Num on Work Combination (unit);
N = Number of Cycle for Loading;
Cms = Excavator Cycle Time (min);
Nm = Excavator Number on Work Combination (unit);
Cmt = Dump Truck Cycle Time (min).

The result will be concluded as follows:

a. MF < 1, the excavator productivity greater than a dump truck, then there is a window time for excavator due to waiting for dump truck;
b. MF = 1, both equipment productivity is same, then there is no window time;
c. MF > 1, the dump truck productivity is more significant than an excavator, then there is a window time for the dump truck to start loading.

Therefore equipment need is determined by the equation:

a. Excavator Need

$$n = \frac{V}{We \times S \times Q} \tag{8}$$

b. Dump Truck Need

$$m = \frac{Q\,\text{excavator}}{Q\,\text{dumptruck}}$$

where:
n = Match Factor;
V = Dump Truck Number on Work Combination (unit);
We = Number of Cycle to Loading;
S = Excavator Cycle Time (min);
Q = Excavator Number on Work Combination (unit).

Whereas to determine work duration follow the equation as:

$$n = \frac{\text{Soil Volume}}{\text{Smallest Equipment Production} \times \text{Work Hour}} \quad (9)$$

To determine heavy equipment operational cost is calculated based on Ministerial Regulation of Public Works and Public Housing Number 28/PRT/M/2016 regarding guidelines for unit prices analysis for work in public works [11].

3 Calculation and Result

3.1 Analysis of Heavy Equipment Productivity Calculation on Zone 1

Analysis of heavy equipment productivity calculation on Zone 1 with the result,

a. **Excavator**

$$\text{Equipment Type} = \text{Komatsu PC 78; Bucket Capacity}\left(q'\right) = 0.34\,\text{m}^3;$$

$$\text{Bucket Factor (k)} = 0.8\ \text{(moderate); Efficiency Factor (E)} = 0.75\ \text{(good)}.$$

Excavator movements time data in zone 1 as in Table 2 is then analyzed using Eq. 1, 2, 3 so that the excavator cycle time the result obtained:

Cycle Time (Cms) = 19.67 s (0.328 min);
Production per cycle (q) = 0.272 m^3;
Excavator Productivity per Hour = 37.34 m^3;
Excavation Productivity per Day = 261.40 m^3/day (7 h per day).

b. **Dump Truck**

Based on the time data for the movement of the dum truck in Table 3 then an analysis was carried out using Eq. 4, 5, 6 and the following data were obtained:

Table 2. Excavator Movements Time Observation Results Zone 1.

Observation Cycle	Movements				
	Digging Time (sec)	Rotating Time Load (sec)	Disposal Time (sec)	Rotating Time Empty (sec)	Total Time (sec)
1	10	5	3	3	21
2	6	4	4	4	18
3	8	5	4	3	20
Average					19.67

Table 3. Dump Truck Movements Time Observation Results Zone 1

Observation Cycle	Movements			
	Speed Loaded Truck (km/ hr)	Speed Empty Truck (km/ hr)	Time to Disposal + stand by time (min)	Time to loading and starting to loading (min)
1	25	29.7	7.8	21.6
2	26	31	8.2	22.2
3	24	29.3	6.7	20.9
Average	25.0	30.0	7.6	21.6

Equipment Type = Dump Truck type Mitsubishi HD 125 PS.
Capacity (C) = 7 m^3.
Distance(D) = 1 km.
Bucket Factor (k) = 1 (clay).

Result analysis:

Window Time + Loading(t1) = 7.6 min Disposal Time (t2) = 21.60 min
Number of Loading Cycle (n) = 20.588 Cycle Time (Cmt) = 40.28 min.
Dump Truck Productivity per hour (Q) = 7.820 m^3.
Productivity per day = 54.74 m^3/day.

3.2 Analysis of Heavy Equipment Productivity Calculation on Zone 2

Productivity Analysis of Heavy Equipment on Zone 2 is determined as follows.

a. **Excavator**

Type = Sany PC 135; Bucket Capacity(q') = 0.53 m^3;
Bucket Factor (k) = 0.8 (moderate); Efficiency Factor (E) = 0.75 (good);

Table 4. Excavator Movements Time Observation Results Zone 2

Observation Cycle	Movements				
	Digging Time (sec)	Rotating Time Load (sec)	Disposal Time (sec)	Rotating Time Empty (sec)	Total Time (sec)
1	10	3	3	4	20
2	12	4	3	4	23
3	15	5	4	3	27
Average					23.33

Table 5. Dump Truck Movements Time Observation Results Zone 2

Observation Cycle	Movements			
	Speed Loaded Truck (km/ hr)	Speed Empty Truck (km/ hr)	Time to Disposal + stand by time (min)	Time to loading and starting to loading (min)
1	24.6	29	6	14
2	25.4	30	6.5	14.8
3	25	31	7	15
Average	25.0	30,0	6.5	14.6

Cycle Time (Cms) = 23.33 s (0.389 min); Production per Cycle(q) = 0.424 m^3;
Excavation Productivity per hour = 49.063 m^3;
Excavation Productivity per day= 343.44 m^3/day.

The calculation results are obtained by analysis using Eq. 1, 2, 3 of the excavator movement time data in Table 4.

b. **Dump Truck**

Type = Dump Truck type Mitsubishi HD 125 PS.
Capacity (C) = 7 m^3.
Distance (D) = 0.5 km.

The calculation results are obtained by analysis using Eq. 4, 5, 6 of the dump truck movement time data in Table 5. Following the results of the analysis that has been carried out.

Loading Speed (V1) = 25 km/hr = 416.68 m/min.
Speed for return(V2) = 30 km/hr = 500.01 m/min.

Bucket Factor (k) = 1 (clay).
Window Time + Loading(t1) = 6.5 min.
Disposal Time (t2) = 14.6 min.
Number of Loading Cycle (n) = 13.208.
Cycle Time (Cmt) = 30.636 min.
Dump Truck Productivity per Hour (Q) = 10.282 m^3.
Productivity per Day = 71.974 m^3/day.

3.3 Analysis of Heavy Equipment Match Factor Calculation on Zone 1

a. **Actual Match Factor Analysis**

The number of excavators used in zone 1 excavation work is 1 unit (Nm), while the dump truck is 3 units (Na). With the excavator cycle time Cms = 0.35 min and the dump truck cycle time Cmt = 40.80 min, then match factor analysis using Eq. (7). Based on the match factor analysis, the value of MF = 0.503 < 1 indicates the excavator's productivity is greater than the dump truck, so there is a window time for the excavator because the dump truck has not arrived yet.

b. **Recommendation Match Factor Analysis**

Based on the actual match factor analysis, the need for heavy equipment analysis that could improve the match factor value was conducted. The investigation resulted in the need for dump trucks for zone 1 excavation work as 5 units and the need for excavators as 1 unit. After recalculation of the match factor, the value of MF = 0.838, which is close to 1, therefore the excavator waiting time is certainly not too long.

3.4 Analysis of Heavy Equipment Match Factor Calculation on Zone 2

a. **Actual Match Factor Analysis**

The number of excavators and dump trucks used in excavation zone 2 is the same as in zone 1. Hence the value of MF = 0.503 < 1, which indicates the excavator's productivity is more significant than a dump truck. Consequently there is a waiting time for the excavator due to the dump truck has not arrived yet.

b. **Recommendation Match Factor Analysis**

Analysis was carried out to produce 5 units of dump truck needs for zone 2 excavation work and 1 unit of excavator needs. After recalculating of the match factor, the value of MF = 0.838, which is close to 1. Hence the excavator waiting time is certainly not too long.

Table 6. Recapitulation of Actual and Recommended Work Duration

Nr.	Work Zone	Actual Duration(Days)	Recommendation Duration (Days)	Margin (Days)
1	Zone 1	22	13	9
2	Zone 2	5	3	2

Table 7. Heavy Equipment Operational Cost

Work Zone	Heavy Equipment	Unit Price (Rp)	Operational Cost /Day (Rp)	
			Actual	Recommendation
Zone 1	Excavator 1	Rp 612,686.00	Rp 94,353,644.00	Rp 55,754,426.00
	Dump Truck	Rp 432,954.00	Rp 200,024,748.00	Rp 196,994,070.00
Total Equipment Operational Cost Zone 1			Rp 294,378,392.00	Rp 252,748,496.00
Zone 2	Excavator 2	Rp 840,953.20	Rp 29,433,362.03	Rp 17,660,017.22
	Dump Truck	Rp 432,954.00	Rp 45,460,170.00	Rp 45,460,170.00
Total Equipment Operational Cost Zone 2			Rp 74,893,532.03	Rp 63,120,187.22

3.5 Work Duration Analysis

The work duration analysis is calculated based on the heavy equipment, which has the smallest productivity, the recapitulation of the calculation results in zones 1 and 2 can be seen in Table 6.

Based on the results above, the recommendation of heavy equipment combination based on the match factor value can lower the duration of work by an average of 40%.

3.6 Heavy Equipment Operational Cost Analysis

The operational costs of heavy equipment were analyzed using the [11] approach and the current price. From the analysis results obtained the operating costs of heavy equipment as shown in Table 3:

As seen in Table 3, the operational cost of the recommendation equipment has a lower total cost than the actual operational cost, causing cutting the duration of work. Average operating costs can be cut by up to 14.9%.

4 Calculation and Result Analysis

Based on the above results, it can be concluded that the combination of heavy equipment based on the match factor value of the actual condition is less than optimal, which is 0.503 and 0.503, respectively, in zone 1 and 2. After re-analysis, the determination of the Number of heavy equipment based on equipment productivity is obtained. The match factor is close to a value of 1, so it can be interpreted that the waiting time from the excavator is not too long. The recommended match factor value is 0.838 in zone 1 and 0.838 in zone 2.

The combination of recommendations also resulted in lower equipment operating costs compared to actual operating costs, and the average cost was reduced by 14.9% (Table 7).

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