Optimizing heavy equipment combination in excavation work of a dam channel construction to support SDG 9: A case study in the Jragung Dam Project

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Abstract. This research aims to analyze the productivity of the excavator and dump truck, evaluate the most efficient combination of excavator and dump truck, and determine the heavy equipment cost required to complete the Jragung Dam channel excavation project. Data collection in this study was carried out using interviews and field observations at the construction site. The results of this study are: (1) excavator productivity was 113.84 m^3/hour and dump truck 29.30 m^3/hour; (2) alternative combination 1 consists of one excavator unit and four dump truck units, alternative combination 2 consists of two excavator units and eight dump truck units, alternative combination 3 consists of three excavator units and twelve dump truck units; (3) the cost of completing the project on alternative 1 requires 4,836 hours and costs for Mitsubishi dump trucks only is IDR 8,147,774,673.48, Hino dump trucks only is IDR 8,368. 444,351.80 and a combination of two types of dump trucks (Hino and Mitsubishi) is IDR 8,368,444,351.80, alternative 2 requires 2418 hours and costs for Mitsubishi dump trucks are IDR 8,121,163,155.04, Hino dump trucks is IDR 8,562,340,865.57, and a combination of two types of dump trucks is IDR 8,341,752,010.31, alternative 3 takes 1612 hours and costs for Mitsubishi dump trucks amounting to IDR 8,116,260,073.48, Hino dump trucks amounting to IDR 8,557,599,430.12, and a combination of two types of dump trucks amounting to IDR 8,336,929,751.80. Alternatives 2-3 with Mitsubishi dump trucks are more suitable for the project as they have shorter work durations and cheaper costs. By optimizing equipment utilization and identifying cost-effective solutions for the Jragung Dam channel excavation, this research contributes to SDG 9 (Industry, Innovation, and Infrastructure) by promoting efficient and sustainable infrastructure development.

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1 Introduction

Indonesia's growing population and economic development have led to rising demands for land and water, which have reportedly increased year after year [1]. The total water demand in Indonesia varies significantly across regions, with Jakarta and other urban areas facing substantial shortfalls in water supply. Regional studies indicate increasing water demand due to population growth and agricultural needs, highlighting the urgent need for improved water management and infrastructure development to meet future demands [2-5].

The current condition of water availability in Indonesia is 56 m^3 per capita per year. This amount is still very small and not much different from the condition of water availability in Ethiopia which is only around 38 m^3 per capita per year. Seeing the condition of water availability, efforts need to be made to accelerate dam construction so that it can meet the community's increasing need for water in Indonesia. One of the efforts made by the Indonesian Government through the Ministry of Public Works and Public Housing to meet water needs is the construction of dams. As of 2017, there were approximately 230 dams in Indonesia with a total capacity of 12.6 billion m^3 [6]. The Ministry of Public Works and Public Housing has a target of building 61 more dams by 2024 [7].

The Jragung Dam in Central Java Province is one of the dams built in Indonesia to enhance the country's water storage capacity. Flow diversion system work was the main emphasis of the Jragung Dam building during the time this research was done. A diversion channel is constructed early in the dam-building process river water flow while the main dam is being built. If the river's flow cannot be redirected, there may be delays in the river-filling project, which could lead to lost time and money. Therefore, the contractor must expedite the work to prevent needless delays and losses.

The use of heavy equipment in construction projects significantly speeds up work, enhances efficiency, and reduces costs [8-9]. However, optimal utilization and proper management are crucial to fully realize these benefits [10]. While heavy equipment improves safety and quality, challenges such as underutilization and high maintenance costs need to be addressed to maximize productivity [11-12]. For the project under this research, considering the condition of the soil at the location where the diversion system is being constructed, which is sandy clay, the heavy equipment chosen for the earth excavation work was excavator(s) and dump trucks.

This research delves into the critical aspects of optimizing heavy equipment utilization for the Jragung Dam Package III diversion channel excavation project. Our primary objective is to conduct a thorough analysis of the excavator and dump truck fleet's productivity. This analysis will involve quantifying factors such as cycle times, loading capacities, and equipment availability, ultimately leading to a clear understanding of each machine's output potential.

Furthermore, the research explored the most efficient equipment combination for the project. This will involve evaluating various scenarios by matching excavator digging capacity with dump truck hauling capabilities. Factors like material density, haul distances, and loading times will be considered to determine the optimal pairing that minimizes idle time and maximizes overall project throughput. Finally, the research aimed to establish the total heavy equipment cost associated with completing the diversion channel excavation. By combining the determined equipment combination with the project's estimated excavation volume and duration, a cost model will be developed. This model will account for factors like equipment rental rates, fuel consumption, and potential maintenance needs, providing a comprehensive cost estimate for the heavy equipment component of the project.

2 Methods

The location of this research is the construction of the Jragung Dam Package III in Semarang Regency, Central Java Province (see **Fig. 1**).

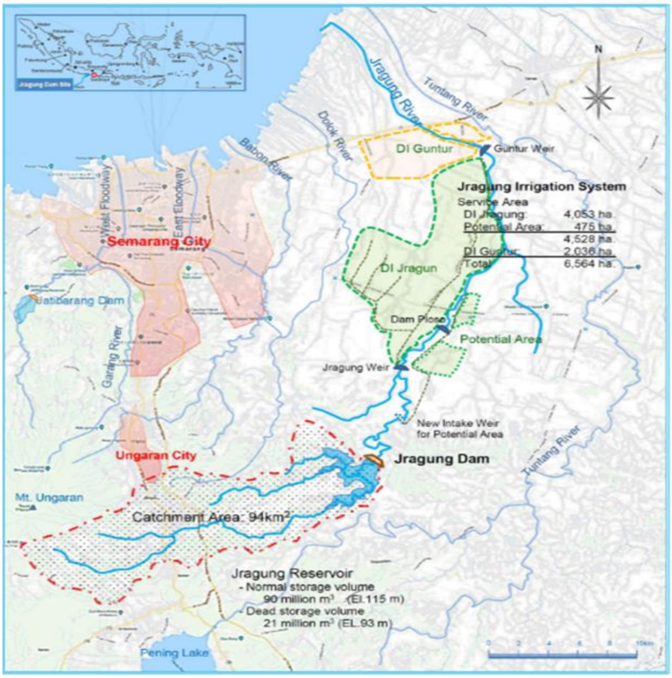

Fig. 1. The research location in Jragung Dam Project

Data were collected by conducting field observations to obtain excavation work cycle times and conducting interviews with technical staff, implementers and mechanics. Supporting data such as project technical data, equipment rental prices and heavy equipment specifications will be analyzed according to the problem identification that has been taken.

The analysis method is carried out by analyzing the cycle time of equipment for excavation work, namely excavators and dump trucks. After obtaining the cycle time, then calculate the equipment productivity value. Next, the heavy equipment rental costs per hour are calculated. After obtaining the productivity values and equipment rental costs per hour, alternative combinations of heavy equipment and the costs required are calculated. Then a comparison of work time and costs will be obtained and then it can be concluded that alternative combinations with the most optimum productivity in terms of time and cost, as an effort to speed up work. The calculation of excavator and dump truck productivity uses the calculation formula from Regulation of the Minister of Public Works and Public Housing No. 1 of 2022 [13] as follows:

$$Q = \frac{V \times F_a \times F_b \times 60}{T_s \times F_k} \qquad (1)$$

Q : excavator productivity per hour (m^3/hour)
V : bucket capacity (m^3)
F_b : bucket factor
F_a : efficiency factor
T_s : cycle time (minutes)
F_k : conversion factor

$$Q = \frac{V x F_a x 60}{T_S} \quad (2)$$

Q : production per hour (m^3/hour)
V : dump truck capacity (m^3)
Fa : dump truck efficiency
Ts : dump truck cycle time (minutes)

The calculation of heavy equipment operational costs is carried out using the equation from the from Regulation of the Minister of Public Works and Public Housing No. 1 of 2022 as follows:

a. Fuel (H) cost

$$H = C_h \text{ x } P_w \text{ x } M_x \quad (3)$$

C_h : fuel coefficient = 0.10
P_w : engine power capacity (HP/horse power)
M_x : price of diesel (IDR/liter)

b. Lubricants (I) cost

$$I = C_p \text{ x } P_w \text{ x } M_p \quad (4)$$

C_p : lubricant coefficient = 0.0025
P_w : engine power capacity (HP/horse power)
M_p : price of lubricants (IDR/liter)

c. Maintenance cost

$$J = C_m \text{ x } B/W \quad (5)$$

J : maintenance/routine maintenance costs (IDR)
B : local cost of equipment (IDR)
W : number of equipment working hours in a year
C_m : maintenance coefficient = 0.022

d. Repairment cost

$$K = C_r \text{ x } B/W \quad (6)$$

K : repair costs (IDR)
B : local cost of equipment (IDR)
W : number of equipment working hours in a year
C_r : improvement coefficient, for:
C_r = 0.064 for light work; C_r = 0.077 for medium work; and C_r = 0.090 for heavy work.

3 Result and Discussion

Calculations of heavy equipment productivity for earth excavation work in the upstream diversion system are carried out to determine the efficiency of time and costs required. The following is an analysis of the productivity of using heavy equipment in earth excavation work.

3.1 Excavator productivity

Excavator *efficiency factor*. In determining the equipment efficiency factors, interviews were conducted with technical and implementing staff who handled the development of the circumvention system. From the interview results, an efficiency factor value of 0.75 was obtained from technical staff and 0.76 from implementers for excavator equipment. The average equipment efficiency factor value was 0.755. An efficiency factor of 0.75 indicates good machine operating and maintenance conditions. Meanwhile, an efficiency factor of 0.76 indicates that the operating conditions of the equipment are very good and machine maintenance is moderate.

Cycle time. The cycle time of the excavator is obtained by direct time measurements in the field. This time was obtained by measuring digging time, swing time, throwing time and swing back time (see Table 1). Based on the measurement results, it was found that the average cycle time for the excavator was 21.01 seconds or 0.3502 minutes.

Table 1. Excavator Cycle Time Measurement

Cycle no.	Time needed (second)				
	Dig	**Swing 1**	**Throw**	**Swing 2**	**Total**
1.	5.26	5.65	7.08	5.48	23.47
2.	6.54	4.83	5.60	5.36	22.33
3.	4.81	4.28	5.18	5.44	19.71
4.	7.24	7.44	5.31	4.10	24.09
5.	5.15	3.72	4.65	5.09	18.61
6.	4.36	6.37	5.53	3.56	19.82
7.	7.12	4.62	6.29	5.05	23.08
8.	5.08	5.16	3.84	5.30	19.38
9.	5.37	4.01	4.17	4.24	17.80
10.	6.73	4.54	5.42	5.12	21.81
Mean	± 5.77	± 5.06	± 5.31	± 4.88	± 21.01

Bucket factor. Based on interviews and observations, it is known that the type of soil in the excavation work is sandy clay with easy digging. Therefore, the bucket factor used in the calculation is 1.1. Using the acquired data and formula (1), the productivity of the excavator used in this project is 113.84 m^3/hour.

3.2 Dump truck productivity

Dump truck efficiency factor. To determine the value of the efficiency factor, interviews were carried out with technical staff and implementers who were responsible for the circumvention building work. From interviews, it was obtained that the dump truck efficiency factor was 0.75 from technical staff and 0.65 from implementers. An efficiency factor of 0.75 indicates good machine operation and maintenance conditions while 0.65 indicates that the operating conditions of the equipment and machine maintenance are moderate. From the two efficiency factor values, an average efficiency factor value of 0.7 is obtained. The condition of dump truck is not able to transport materials according to the capacity of the vessel because the hilly road terrain that is traversed to get to the disposal area is one of the obstacles that has to be faced. Apart from the hilly terrain, the road mostly consists of clay when rainy conditions cause the road terrain to be slippery so the load volume cannot be maximized for safety reasons.

Dump truck cycle times. It is obtained through direct observation of the field loading time, waiting time for dumping, dumping time, return time, waiting time for loading, and time to take position (Table 2). Based on field observations, the average dump truck cycle time was 17 minutes 12 seconds or 17.20 minutes.

Table 2. Dump Truck Cycle Time Measurement

Cycle no.	Time needed (minute)						Total
	Load	**Transport**	**Wait + Dump**	**Return**	**Wait**	**Loading position**	
1.	00:03:01	00:05:58	00:01:58	00:04:35	00:01:39	00:00:42	00:17:53
2.	00:03:21	00:05:49	00:02:15	00:04:22	00:01:04	00:00:20	00:17:11
3.	00:02:58	00:06:06	00:01:53	00:04:09	00:02:01	00:00:37	00:17:44

Cycle no.	Time needed (minute)						Total
	Load	Transport	Wait + Dump	Return	Wait	Loading position	
4.	00:03:13	00:06:53	00:02:03	00:05:05	00:01:49	00:00:31	00:19:34
5.	00:02:30	00:05:30	00:02:12	00:04:25	00:01:02	00:00:32	00:16:11
6.	00:02:07	00:05:23	00:01:50	00:04:11	00:01:35	00:00:45	00:15:51
7.	00:02:18	00:05:02	00:02:04	00:04:02	00:01:27	00:00:39	00:15:32
8.	00:03:25	00:05:04	00:02:11	00:04:59	00:01:05	00:00:35	00:17:19
9.	00:03:19	00:05:13	00:01:41	00:04:36	00:01:40	00:00:50	00:17:19
10.	00:03:23	00:06:12	00:01:52	00:04:34	00:00:55	00:00:31	00:17:27
Mean	00:02:58	00:05:43	00:02:00	00:04:30	00:01:26	00:00:36	00:17:12

Using the acquired data and formula (2), the productivity of the excavator used in this project is 29.30 m^3/hour.

3.3 Heavy equipment operational costs

Based on the results of interviews regarding the heavy equipment rental contracts used, the operational costs borne by the contractor are the costs of fuel, lubricants, repairs, maintenance and operators. The calculation of total equipment rental costs is done by adding the equipment rental costs to the equipment operational costs. The calculation of total operational costs for excavator heavy equipment is obtained as follows:
Total equipment operating costs = operational costs (fuel, lubricants, repairs, care and maintenance, as well as operator wages) + rental costs.

Excavator and dumptruck cost. The basis for excavator and dumptruck cost calculation is presented in Table 3 and Tabel 4.

Table 3. List of equipment price, fuel, lubricants, and labor costs for excavator operation

No	Description	Price	Source
1.	Equipment rental cost	IDR 536,000.00/hour	PT. Brantas Abipraya (company)
2.	Local price for equipment	IDR 1,156,100,000.00	Ministry of Public Work 09/PRT/M/2014
3.	Operator fee	IDR 122,000.00/8 hour IDR 15,250/hour	Semarang Regency Decree Number 51 Tahun 2022 [14]
4.	Fuel price	IDR 6,800.00/liter	PT. Pertamina Tbk
5.	Lubricant price	IDR 56,100.00/liter	PT. Pertamina Lubricants

Table 4. List of equipment price, fuel, lubricants, and labor cost for dump truck operation

No	Description	Price	Source
1.	Equipment rental cost	IDR 310,000.00/hour	PT. Brantas abipraya
2.	Local price for equipment - Mitsubishi - Hino	 IDR 1,108,000,000.00 IDR 1,283,000,000.00	oto.com
3.	Operator fee	IDR 122,000.00/8 hour IDR 15,250/hour	Semarang Regency Decree Nomor 51 Tahun 2022
4.	Fuel price	IDR 6,800.00/liter	PT. Pertamina
5.	Lubricant price	IDR 56,100.00/liter	PT. Pertamina Lubricants

After applying formula (2) to (6), the total operational cost for excavator and dump truck is summarized in Table 5 and Table 6.

Table 5. Summary of excavator operational costs

No	Description	Code	Unit	Cost
Equipment Detail				
1.	Type of equipment			Excavator
2.	Vehicle brand/type			Komatsu PC-200
3.	Power	P_w	HP	138
4.	Bucket capacity	C_p	m^3	1
5.	Year			2020
A. Rental cost			IDR/Hour	**IDR 536,000.00**
B. Operational cost				
1.	Fuel	H	Hour	IDR 93,840.00
2.	Lubricants	I	Hour	IDR 19,354.50
3.	Maintenance	J	Hour	IDR 12,717.10
4.	Reparation	K	Hour	IDR 36,995.20
5.	Operator fee	L	Hour	IDR 15,250.00
	Operational cost: H+I+J+K_L		IDR/Hour	**IDR 178,156.80**
C. Total cost: A+B			IDR/Hour	**IDR 714,156.80**

Table 6. Summary of dump truck operational costs

No	Description	Code	Unit	Cost	
Equipment Detail					
1.	Type of equipment	Dump truck			
2.	Vehicle brand/type			Mitsubishi	Hino
3.	Power	P_w	HP	215.6	254.8
4.	Bucket capacity	C_p	m^3	24	24
5.	Year			2018	2018
A. Rental cost			IDR/Hour	**IDR 310.000,00**	**IDR 310,000,00**
B. Operational cost					
1.	Fuel	H	Hour	IDR 146,608.00	IDR 173,264.00
2.	Lubricants	I	Hour	IDR 30,237.90	IDR 35,735.70
3.	Maintenance	J	Hour	IDR 12,188.00	IDR 14,113.00
4.	Reparation	K	Hour	IDR 35,456.00	IDR 41,056.00
5.	Operator fee	L	Hour	IDR 12,250.00	IDR 12,250.00
	Operational cost: H+I+J+K+L		IDR/Hour	**IDR 239,739.90**	**IDR 279,418.70**
C. Total cost: A+B			IDR/Hour	**IDR 549,739.90**	**IDR 589,418.70**
D. Mean cost			IDR/Hour	**IDR 569,579.30**	

3.4 Analysis of Alternative Heavy Equipment Combinations

The results of productivity analysis and cost analysis can be used as an alternative combination of heavy equipment use. The following is an alternative combination of using heavy equipment for earth excavation work.

Alternative 1. In alternative 1, heavy equipment is used in the form of a PC-200 excavator unit with a bucket capacity of 1 m^3 with the number of dump trucks adjusting the productivity of the excavator for each excavation. The following are alternative heavy equipment combinations.

Alternative 2. In alternative 2, heavy equipment is used in the form of two PC-200 excavator units with a bucket capacity of 1 m^3 with the number of dump trucks adjusting the productivity of the excavator at each excavation. The following are alternative heavy equipment combinations.

Alternative 3. In alternative 3, heavy equipment is used in the form of three PC-200 excavator units with a bucket capacity of 1 m^3 with the number of dump trucks adjusting the productivity of the excavator at each excavation. The following are alternative heavy equipment combinations.

Based on the results of calculations that have been carried out; to complete the open ground excavation work for the upstream direction channel, the excavator productivity was 113.84 m^3/hour and the dump truck productivity was 29.30 m^3/hour. The results of cost calculations and work duration for each alternative are presented in Table 7.

Table 7. Cost calculations and work duration for each combination alternative

Description	*Dump Truck type*	Total Cost	Duration (hour)
Existing construction work	Combination of both Mitsubishi and Hino DTs	IDR 8,229,874,833.28	4297
Alternative 1	Mitsubishi DTs only	IDR 8,147,774,673.48	4836
	Hino DTs only	IDR 8,589,114,030.12	
	Combination of both DTs	IDR 8,368,444,351.80	
Alternative 2	Mitsubishi DTs only	IDR 8,121,163,155.04	2418
	Hino DTs only	IDR 8,562,340,865.57	
	Combination of both DTs	IDR 8,341,752,010.31	
Alternative 3	Mitsubishi DTs only	IDR 8,116,260,073.48	1612
	Hino DTs only	IDR 8,557,599,430.12	
	Combination of both DTs	IDR 8,336,929,751.80	

4 Conclusion

Based on the results and studies that have been carried out, the following conclusions can be obtained: (1) The productivity of heavy equipment obtained in the upstream direction channel excavation work was an excavator of 113.84 m^3/hour and a dump truck of 29.30 m^3/hour. (2) Alternative combinations of excavator and dump truck heavy equipment used in excavation work for the diversion channel of the Jragung Package III Dam construction project in the upstream section are as follows: (a) Alternative 1, the number of excavators used is one unit and 4 dump trucks. This combination produces excavator and dump truck productivity of 113.84 m^3/hour. Combination of alternative 1 with one excavator and four dump trucks, the work was completed in 4836 hours. The cost of using the Mitsubishi dump truck type is IDR 8,147,774,673.48, a Hino dump trucks IDR 8,147,774,673.48, and a combination of both dump truck is IDR 8,368,444,351.80. (b) Alternative 2, the number of excavators used is two units and eight dump trucks. The productivity of excavators and dump trucks is 227.69

m^3/hour. Alternative combination 2 with two excavators and eight dump trucks, the work was completed in 2418 hours. The cost of using Mitsubishi dump trucks is IDR 8,121,163,155.04, Hino dump trucks is IDR 8,562,340,865.57, and a combination of both dump trucks is IDR 8,341,752,010.31. (c) Alternative 3, the number of excavators used is three units and twelve dump trucks. The productivity of excavators and dump trucks is 341.53 m3/hour. Alternative combination 3 with three excavators and twelve dump trucks can work in 1612 hours. The cost of using Mitsubishi dump trucks is IDR 8,116,260,073.48, Hino dump trucks is IDR 8,557,599,430.12, and a combination both dump trucks is IDR 8,336,929,751.80. (3) By optimizing equipment utilization and identifying cost-effective solutions for the Jragung Dam channel excavation, this research contributes to SDG 9 (Industry, Innovation, and Infrastructure) by promoting efficient and sustainable infrastructure development. The findings of this study can inform future infrastructure projects by providing insights into equipment productivity, cost optimization, and project duration, ultimately leading to improved resource management and economic efficiency.

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