Optimization of heavy equipment for earthwork in the construction of Mainroad Section X of Pandaan-Malang Toll Road

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Abstract. The construction of Mainroad Section X of Pandaan-Malang Toll Road requires of heavy equipment for excavation and embankment works. The type and number of the heavy equipment can be varied depending upon the construction volume, equipment capacity, and the budget. Therefore, the combination of heavy equipment must be chosen carefully to minimize the cost. This study aims to determine the optimum number of heavy equipment combinations with constraints of work volume, schedule, and resources availability to minimize the construction cost. The data needed is site lay-out plan, cross section of the road, project time schedule, specifications of the heavy equipment, and the resources unit price. The method for optimization is Linear Programming using Simplex Method. The results shows that the optimum combination of heavy equipment for excavation work are 14 units of bulldozer type Zoomlion ZD160-3, 5 unit excavator type Komatsu PC200-8MO, and 19 units dump trucks type Mitsubishi Fuso-FN627 at Rp 14.839.362.044,00. As for the embankment work, the optimum equipment are 5 units excavators type Komatsu PC200-8MO, 19 units of dump truck type Mitsubishi Fuso-FN627, 19 units of motor grader type Caterpillar 120K, 18 units of sheep foot roller type Ammann ASC-200, and 23 units of water tank truck type Mitsubishi-125HD at Rp 22.979.058.760,00.

1. Introduction
The Toll Road Construction Project of Pandaan-Malang region is the extension of the Trans Java Toll Road Project which connect Surabaya - Pandaan - Malang. Considering its huge volume of workloads, specific methods, and large cost, the Pandaan-Malang Toll Road construction project requires an effective method of implementation. The mainroad’s earthwork uses heavy equipment to ease and improve the work, hence it must be managed accordingly to avoid its idleness, which could increase the equipment cost. By taking the work and length of this project into consideration, this study only observes the mainroad section X of Pandaan - Malang Toll Road.

This study aims to determine the optimal combination of heavy equipments usage with minimum cost for mainroad’s earthwork. Optimization problems can be solved by using the linear programming method which is an optimization technique and a linear constraint system that aims to maximize profits or minimize costs, restricted by certain limitations [1]. Optimization problems using linear programming sometimes involve many constraints and variables, thus a series of mathematical procedures is needed to find solutions to more complex problems. The procedure that can be used is the simplex method [2].
Similar research has been conducted by several people, namely: Yadam [3] who found optimum cost of Suzuki Negara Stock Yard Development Project, Bali of Rp. 560,960,000; Maddeppungeng et al. [4] who found optimum cost of Port Development Projects of PT. Cemindo Gemilang of Rp. 10.395.810.000; Wibowo and Zacoeb [5] who found optimum cost of Villa Bukit Tidar Malang Housing Project of transportation cost of Rp.248.296.400, and embankment cost of Rp.111.571.400; and Suhendra et al. [6] who found optimum cost of Providing Selected Landfills for Improving Network Access of Clean Water Pipeline Network in West Tanjung Jabung Regency, Booster Senyerang reduced cost of Rp.6.455.000.

The most crucial step in linear programming is to formulate a linear program. This step includes identifying goals and boundaries. Some elements commonly used are the formulation of decision variables, objective functions, constraint functions, and variable constraints [1].

The standard linear programming problems are as follows [7]:

Maximize or minimize

\[ Z = c_1 x_1 + c_2 x_2 + c_3 x_3 + \cdots + c_j x_j \]  \hspace{1cm} (1)

Limiting resources (constraints):

\[ z a_{11} x_1 + a_{12} x_2 + a_{13} x_3 + \cdots + a_{1j} x_j \leq b_1 \]  \hspace{1cm} (2)
\[ a_{21} x_1 + a_{22} x_2 + a_{23} x_3 + \cdots + a_{2j} x_j \leq b_2 \]
\[ \vdots \]
\[ a_{j1} x_1 + a_{j2} x_2 + a_{j3} x_3 + \cdots + a_{jn} x_j \leq b_i \]

Where \( c_j \) = cost per unit for each \( x_j \); \( x_j \) = the \( j^{th} \) decision variable; \( a_{ij} \) = the \( i \) resource requirements for each \( x_j \); \( b_i \) = number of available resources; \( j \) = number of decision variables, starting from 1,2,3…j; and \( i \) = number of resources usage, starting from 1,2,3…i.

In the use of heavy equipment, it is necessary to pay attention to the type of heavy equipment used, knowledge of the capacity and capability of heavy equipment in order to meet the requirements of use, namely not causing a waste of labor, capital, and meeting safety needs [8]. Equipment cost per unit is also determined by the productivity. To calculate the productivity of each heavy equipment used [9]:

a. Excavator productivity:

\[ Q = \frac{V \times F_a \times F_b \times 60}{T_s \times F_y} \]  \hspace{1cm} (3)

Where \( V \) = bucket capacity; \( F_a \) = the tool’s efficiency factor; \( F_b \) = bucket factor; \( T_s \) = cycle time; \( F_y \) = conversion factor; and 60 is hour to minute conversion.

b. Dump truck productivity:

\[ Q = \frac{V \times F_a \times 60}{D \times T_s} \]  \hspace{1cm} (4)

Where \( V \) = body capacity; \( F_a \) = the tool’s efficiency factor; \( F_k \) = material construction factor; \( D \) = material mass (loose); \( T_s \) = cycle time; and 60 is hour to minute conversion.

c. Bulldozer productivity; stripping work:

\[ Q = \frac{q \times F_b \times F_m \times F_a \times 60}{T_s} \]  \hspace{1cm} (5)

and leveling work:

\[ Q = \frac{l \times (n(L - Lo) + Lo) \times F_b \times F_m \times F_a \times 60}{N \times n \times T_s} \]  \hspace{1cm} (6)
Where $q$ = stripping capacity; $F_b$ = blade factor; $F_m$ = blade inclination factor; $F_a$ = the tool’s efficiency factor; $l$ = stripping distance; $n$ = number of paths; $L_o$ = overlap width; $N$ = number of stripping paths; $T_s$ = cycle time; and 60 is hour to minute conversion.

d. Sheep foot roller productivity:

$$Q_p = W_e \times V \times H \times 1000 \times \frac{E}{N}$$

Where $Q_p$ = sheep foot roller productivity; $W_e$ = effective compaction width; $V$ = average tool’s velocity; $H$ = compaction thickness; $E$ = tool’s efficiency factor; $N$ = number of paths; and 1000 is km to m conversion.

e. Motor grader productivity; leveling work:

$$Q = \frac{L_h \times \{n(b - b_0) + b_0\} \times F_a \times 60}{N \times n \times T_s}$$

and leveling solid overlay:

$$Q = \frac{L_h \times \{n(b - b_0) + b_0\} \times F_a \times 60 \times t}{N \times n \times T_s \times F_k}$$

Where $L_h$ = the stretch length; $n$ = number of paths; $b_0$ = overlap width; $F_a$ = work efficiency factor; $N$ = number of stripping per track; $T_s$ = cycle time; $t$ = solid overlay thickness; $F_k$ = material construction factor; and 60 is hour to minute conversion.

f. The water tank truck productivity:

$$Q = \frac{P_a \times F_a \times 60}{W_c \times 1000}$$

Where $P_a$ = water pump capacity; $F_a$ = tool’s efficiency factor; $W_c$ = water needs per m3 solid material; 60 is hour to minute conversion; and 1000 is km to m conversion.

The calculation of the rental and operational costs of each heavy equipment per hour is as follows [9]:

a. Definitive cost:

$$G = (E + F) = \frac{(B - C) \times D}{W} + \frac{lns \times B}{W} = \frac{(B - C) \times D + (lns \times D)}{W}$$

Where $G$ = hourly estimated cost (Rp); $E$ = capital return cost; $F$ = insurance, taxes, and other cost/year; $B$ = local cost of equipments; $C$ = tool’s residual value; $D$ = installment/return factor; $W$ = number of equipments working hour/year, $lns$ = Insurance (%).

b. Operational cost:

$$P = H + I + J + K + L + M$$

Where $H$ = fuel usage (liter)/hour; $I$ = lubricant usage (liter)/hour; $J$ = workshop maintenance cost/hour; $K$ = service cost/hour including parts replacement; $L$ = operator/driver’s hourly wage/hour; $M$ = assistant operator/driver’s hourly wage/hour.

One of the computer applications that can easily, quickly and accurately solve linear programs is LINDO (Linear Interactive Discrete Optimizer) software. The main working principle of the LINDO program is entering formulas, solving them and estimating the correctness and appropriateness of formulas based on their solutions [10].
2. Methods
The optimization of heavy equipment usage for main road section X of Pandaan-Malang Toll Road consist of several stages. The first stage is collecting secondary data such as site plan drawings, cross section drawings, specifications and types of heavy equipment as well as its pricelist, and the project master schedule. The next stage are identifying the type of earthworks; which consists of excavation and embankment work, then calculating the volume based on cross section data, determining the method to carry out excavation and embankment work, determining the type of heavy equipment that can be used according to work conditions and calculate its productivity, determining the combination of heavy equipment for existing conditions and alternative combinations [11], then calculating its cost, respectively. The above data are used to determine the optimal heavy equipment usage for earthworks using linear programming with simplex method in the form of decision variables, objectives, and constraints as well as transforming those variables into objective and constraints functions. In order to minimize the heavy equipment cost, the objective and constraints function are transformed into a standard model according to the provisions of LINDO 6.1 to yield the optimized solution.

3. Results and discussion

3.1. Work volume calculation

![Detailed Structure](image1)

![Movement of Heavy Equipment](image2)

**Figure 1.** Detailed structure of mainroad works and movement of heavy equipment.

The excavation volume defines the required amount of peat soil to be disposed from the former paddy fields, ranging from STA 35+375 – STA 38+488 as deep as 30 cm. The calculation was based on the cross-section data, which resulting excavation volume of 158.355 m³ and soil embankment volume of 696.776 m³. Figure 1 below shows the detailed structure of main road works.

3.2. Excavation work method
The excavation work aims to disposing peat soil from the embankment location to disposal area, by stripping the surface soil on former paddy fields. The heavy equipment used are bulldozer, excavator, and dump truck. The movement flow of each heavy equipment used in excavation work is illustrated in Figure 1(b). As the bulldozer clears the location, it moves forward; pushing the excavated ground and cleans the location towards the excavator’s rotation area, in back and forth motion. The excavator only rotates 180º, processing the loaded excavation material into a dump truck. The dump truck queues the loading process at the site, process the loading from excavator, transports the excavation materials to quarry location, disposes the material at the quarry location, and travels back to the project site, respectively.

3.3. Embankment work method
The embankment work which carried out through the STA. 35+375 – STA 38+488, aims to achieve the desired elevation by using materials from the borrow area. The heavy equipment used for this work are excavator, dump truck, motor grader as the landfill spreader tool, sheep foot roller as the soil compactor, and water tank truck as watering tool. The work includes soil extraction from the quarry using excavator which then transported to the project site by dump truck, laying each layer of materials using motor grader, then levelled by the bulldozer. The sheep foot rollers and water tanks then work simultaneously to achieve the desired solid embankment as planned.
The movement flow of each heavy equipment used in embankment work is: the excavator processes the loading excavated soil into a dump truck, thus it only rotates 180°. The dump truck queues the loading process at the quarry, processes the loading from excavator, transports the materials to project site, dumps the materials at the project site, respectively in back and forth motion. The motor grader moves forward to level the soil, also in back and forth motion. The sheep foot roller and water tanks simultaneously compact and watering the soils in forward and backward motions.

3.4. Selection of heavy equipment
The selected heavy equipment used in the mainroad earthwork based on Ministry of Public Works [11], are EXT1 (Excavator - Caterpillar 320D2), EXT2 (Excavator - Komatsu PC 200-8MO), DT1 (Dump Truck - Hino FM 260JM), DT2 (Dump Truck - Mitsubishi Fuso FN 627), BD1 (Bulldozer - Zoomlion Zd 160-3), BD2 (Bulldozer - Komatsu D85E SS-2 Angle Dozer), SFR1 (Sheep Foot Roller - Ammann ASC-200), MG1 (Motor Grader - Caterpillar 120 K), MG2 (Motor Grader - Mitsubishi MG330), WTT1 (Water Tank Truck - Mitsubishi 125HD).

3.5. Calculation of productivity and equipment cost

Table 1. Heavy equipment productivity and rental and operating cost.

| Excavation (m3/hour) | Embankment (m3/hour) | Operational Rental Price / hour | Mobilization Fee |
|----------------------|----------------------|-------------------------------|-----------------|
| BD1 65.652           |                      | Rp 696,608                    | Rp 3,775,000    |
| BD2 64.740            |                      | Rp 729,112                    | Rp 3,775,000    |
| EXT1 160.551 EXT1    | 160.551              | Rp 844,647                    | Rp 5,285,000    |
| EXT2 147.266 EXT2    | 147.266              | Rp 625,052                    | Rp 5,285,000    |
| DT1 20.659 DT1       | 13.616               | Rp 863,130                    | Rp 566,250      |
| DT2 20.659 DT2       | 13.616               | Rp 814,435                    | Rp 566,250      |
| MG1 27.321           |                      | Rp 811,686                    | Rp 3,775,000    |
| MG2 34.471           |                      | Rp 837,075                    | Rp 3,775,000    |
| SFR1 104.197         |                      | Rp 782,856                    | Rp 3,775,000    |
| WTT1 71.143          |                      | Rp 439,074                    | Rp 566,250      |

The heavy equipment productivity presented at Table 1, are calculated using Equation 3-10. Since each type of equipment used has rental, operational, and mobilization cost, the total equipment cost at Table 1 are calculated using Equation 11-12. Calculation of wages and equipment rental costs based on AHSPK [12].

3.6. Heavy equipment alternative combination

Table 2. Alternative combinations of heavy equipments.

| Alternative | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------------|---|---|---|---|---|---|---|---|
|             |  | DB1| DB1| BD1| BD2| BD2| BD2| BD2|
|             | EXT1| EXT1| EXT2| EXT2| EXT1| EXT2| EXT2| EXT2|
|             | DT1| DT2| DT1| DT2| DT1| DT2| DT1| DT2|
|             | EXT1| EXT1| EXT2| EXT2| EXT1| EXT2| EXT2| EXT2|
|             | DT1| DT2| DT1| DT2| DT1| DT2| DT1| DT2|
|             | MG1| MG1| MG1| MG1| MG2| MG2| MG2| MG2|
|             | SFR1| SFR1| SFR1| SFR1| SFR1| SFR1| SFR1| SFR1|
|             | WTT1| WTT1| WTT1| WTT1| WTT1| WTT1| WTT1| WTT1|

The alternative combination of heavy equipment are selected based on available types and specifications [11], which then optimized accordingly. Determining the combination of heavy equipment are the work volume, limited project site area, and each of equipment’s dependency. The existing combination is described as alternative 1 in Table 2, followed by alternative combinations 2-8.
3.7. Optimization

Aiming to get the optimum number of each heavy equipment for the mainroad earthwork as well as its minimum cost, the optimization of excavation and embankment work are carried out separately by considering the differences in working conditions and characteristics.

3.7.1. Optimization for excavation work (Alternative 1)

The three pre-determined main factors are: Decision variables: X1 = Number of DB1 units; X2 = Number of EXT1 units; and X3 = Number of DT1 units; Objective function: referring the Equation 1 and Table 2, Z min = 696,608X1 + 844,647X2 + 863,130X3; and Constraints function: Excavation volume constraints: 65.652 X1 ≥ 306.269; 160.551 X2 ≥ 306.269; and 20.659 X3 ≥ 306.269; Area constraints: 383X1 + 1327X2 + 636X3 ≤ 281250; 6.630X1 ≤ 90; 18.760X2 ≤ 90; and 4.955X3 ≤ 90; Equipment dependency constraints: 10X1 + 4X2 + 31X3 ≥ 158353.4; and Non-negativity constraints: X1, X2, X3 ≥ 0. The optimization for excavation work yields BD1 = 14 units, EXT1 = 5 units, and DT1 = 19 units as the number of heavy equipment per hour with minimum cost of Rp. 30,375,207.

3.7.2. Optimization for embankment work (Alternative 1)

Table 3. Recapitulation of total heavy equipment cost for excavation work and embankment work.

| Alt | Volume (m³) | Hour | Optimum Number of Unit/Hour | Productivity (m³/Hour) | Rental Cost/Hour (Rp) | Total Rental Cost (Rp) |
|-----|-------------|------|----------------------------|------------------------|----------------------|------------------------|
| 1   | 158,355     | 14   | 5                          | 19                     | 65.65                | 30.375,207             | Rp 180,067,500         |
| 2   | 158,355     | 14   | 5                          | 19                     | 65.65                | 29.450,016             | Rp 180,067,500         |
| 3   | 158,355     | 14   | 5                          | 19                     | 147.27               | 27.321                 | Rp 180,067,500         |
| 4   | 158,355     | 14   | 5                          | 19                     | 147.27               | 27.321                 | Rp 180,067,500         |
| 5   | 158,355     | 14   | 5                          | 19                     | 147.27               | 27.321                 | Rp 180,067,500         |
| 6   | 158,355     | 14   | 5                          | 19                     | 147.27               | 27.321                 | Rp 180,067,500         |
| 7   | 158,355     | 14   | 5                          | 19                     | 147.27               | 27.321                 | Rp 180,067,500         |
| 8   | 158,355     | 14   | 5                          | 19                     | 147.27               | 27.321                 | Rp 180,067,500         |

This following model for alternative 1 is calculated on LINDO: Min = 844647X1 + 863130X2 + 811686X3 + 969608X4 + 439074X5; 160.551 X1 = 1746.902; 13.616 X2 = 1746.902; 27.321 X3 = 1746.902; 104.197 X4 = 1746.902; 71.143 X5 = 1746.902; 1327X1 + 295X2 + 348X3 + 289X4 + 117X5 <= 281250; 18.760X1 <= 90; 4.955X2 <= 90; 4.895X3 <= 90; 5.100X4 <= 90; 4.020X5 <= 90; 4X1 + 47X2 + 24X3 + 6X4 + 9X5 >= 0; X1, X2, X3, X4, X5 >=0. The optimization for embankment work yields EXT1 = 5 units, DT1 = 19 units, MG1 = 19 units, SFR1 = 18 units, and WTT1 = 23 units, as the number of heavy equipment per hour with minimum cost of Rp. 58,682,263. Following the same calculation for other alternative combinations, each optimum cost per hour for each combination. The total cost of each Excavation and embankment work equipment can be calculated by multiplying the duration of the work per hour with operational costs and additional mobilization costs, hence the results are presented in Table 3. Based on Table 3, it is known that alternative 4 (gray block) is the best alternative for excavation work with a minimum cost of Rp. 14,839,362,044, - and alternative 4 (gray block) is also the best alternative with a minimum cost of Rp. 22,979,058,760.
4. Conclusions

Based on the results of the calculation using LINDO, the study findings can be concluded as follows:

- The optimum alternative for excavation work is alternative 4 with total cost of Rp. 14,839,362,044, following the combination of 14 units Bulldozer Type Zoomlion ZD 160-3 Type, 5 units Excavator Type Komatsu PC 200-8MO, and 19 units Dump Trucks Type Mitsubishi Fuso FN 627.

- The optimum alternative for embankment work is alternative 4 with total cost of Rp. 22,979,058,760, following the combination of 5 units Excavators Type Komatsu PC 200-8MO, 19 units Dump Trucks Type Mitsubishi Fuso FN 627, 19 units Motor Graders Type Caterpillar 120 K, 18 units Sheep Foot Rollers Type Ammann ASC-200 Type, and 23 Units Water Tank Trucks Type Mitsubishi 125HD.

It is expected that the further research can present more varied alternative combinations of heavy equipment according to the types of equipment available in the catalogue to improve optimization results. Furthermore, we need to pay more attention to the limitations on the field in order to formulate the overall constraints. The contractor is advised to use combination IV as a combination of heavy equipment used for excavation and landfill in the project, which described in the conclusion so that the contractor can minimize heavy equipment usage cost.

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