Research on methods for effective use of machines in kit in construction and repair of asphalt concrete pavement

Zakir Maksudov*, and *Mavlyan* Kudaybergenov

Tashkent State Transport University, Tashkent, Uzbekistan

Abstract. This paper develops a methodology for studying the effective use of asphalt paving and transport machines, the main determining parameters of which are the cost and productivity of transporting and laying asphalt concrete mix. An algorithm has been developed for optimizing the operational performance of a set of asphalt paving and transport machines in the construction and repair of roads.

1 Introduction

Improving the efficiency of road construction machines and road transport in an interconnected set of machines in the construction and repair of highways is an urgent task.

Research and determination of the optimal number of dump trucks in the asphalt-laying and transport set of machines is a technical and economical task, in solving which it is necessary to consider the duration of downtime of all parts of the set and its impact on the performance of the set and the cost of a unit of production (in this case, 1 m3 of asphalt concrete mix).

2 Materials and methods

The problem under consideration is the type of queuing tasks in closed systems. The source of the maintenance requirements is an asphalt paver; maintenance is performed by a MAN TGL 26. 280 dump truck. Depending on the number of dump trucks included, the duration of their downtime and the t_a of the paver will vary, which, in turn, will affect the cost of transportation and laying of 1 m^3 of asphalt concrete mixture. The minimum cost value and the optimal number of dump trucks in the set are determined in [1-7].

The cost of loading and transporting 1 m^3 of asphalt concrete mix can be determined as follows:

$$C_e = \frac{\gamma}{2GK_{uf}K_{fc}} \cdot [C_{m-h.dt}(T_{cd} + t_{dt}) + 2C_k L] + \frac{C_{m-h.ap}}{P_e} + W_p + C_{ac} \quad (1)$$

where, γ is the volume mass of asphalt concrete mix, kg/m^3, we accept γ = 1800 kg/m^3; G is load capacity of the dump truck, kg, G = 16.0 t; K_{fc} is the utilization factor of the load

* Corresponding author: maksudov-55@mail.ru

capacity of the dump truck; K_{uf} - the mileage utilization factor of the dump truck; $C_{m-h.dt}$ is the cost of mash.-hours of operation of the dump truck, independent of its mileage, sum/h; T_{cd} is the duration of the working cycle of the dump truck, h; t_{dt} is the duration of downtime of the dump truck, h; C_k is the cost of 1 km of the run of a dump truck, sum/km; L is the distance of soil transportation, km; $C_{m-h.ap}$ is costs for 1 machine-hours of work of an asphalt paver for laying asphalt concrete mix, sum/h; P_e is the operational capacity of a set of machines, m^3/h; W_p is wages of auxiliary workers per 1 m^3 of asphalt concrete mix, sum/m^3; C_{ac} is the cost of 1 m^3 of asphalt concrete mix, sum/m^3.

The operational performance of an asphalt-laying and transport set of machines for the installation of asphalt concrete pavement [8-10], taking into account the duration of downtime of loading machines, can be determined from the expression:

$$P_e = \frac{G \cdot K_t \cdot K_{or} \cdot K_{fc}}{\gamma \cdot (T_{ca} + t_d)} \tag{2}$$

where, K_t is a coefficient that takes into account the loss of time due to technical reasons (due to the elimination of failures and malfunctions, maintenance, etc.); K_{or} is a coefficient that takes into account the loss of time for organizational reasons (due to the lack of front work, electricity, materials, etc.); T_{ca} is the duration of the working cycle of the paver for laying asphalt concrete mix, h; t_d is the duration of downtime of the paver waiting for the arrival of the dump truck, h.

The optimal number of dump trucks should ensure the maximum performance of the kit with a minimum cost of transportation and laying of 1 m3 of asphalt concrete mix. There are two ways to solve this problem: statistical modeling (Monte Carlo method); graphic-analytical method [11-13].

When determining the optimal number of dump trucks in a set by statistical modeling, sequential multiple calculations of the performance of the set and the cost of loading and transporting asphalt concrete mixture are performed according to formulas (1) and at different values t_a and t_{dt}.

The values of variables t_a and t_{dt} are selected following the known laws of the distribution of these quantities. The type of distribution laws t_a and t_{dt} is taken based on the timekeeping results or by analogy with previously conducted studies.

Thus, the task is consistently "played" with different source data. The number of dump trucks *N*, providing a minimum cost value of C_e is considered optimal [14-17].

To simplify calculations during optimization, they operate not with random values of indicators (for example, the cycle duration of a dump truck) selected following the law of their distribution but with mathematical expectations of these indicators [18-21]. The random nature and type of the law of distribution of random variables are considered when determining the boundaries of the interval of optimal values of the desired indicators: the number of machines, the productivity of the set, and the cost of 1 m^3 of asphalt concrete mix.

The calculation of values P_e and C_e is made for 2...10 arbitrary values of *N*. Based on the results of the calculations, dependency graphs are built:

$$P_e = \varphi \cdot (N_i);\ C_e = \varphi \cdot (N_i) \tag{3}$$

According to schedule $C_e = \varphi \cdot (N_i)$ the minimum value C_e and the number of dump trucks N_{opt} corresponding to this value are determined.

The calculation of the optimal number of dump trucks by the graphical-analytical method is carried out in the following sequence.

1. The duration of the working cycle of a dump truck is determined without considering the loading time according to the formula:

$$T_{cd} = 2\frac{L}{V_c} + t_u \quad (4)$$

where, t_u is auxiliary time for unloading, turns, etc., t_u = 0.05 h; V_c is capture length, km/h.

1. The duration of the dump truck cycle is compared with the total time it is under unloading:

$$- \quad T_{cd} > \frac{t_p \cdot N}{n} \quad (5)$$

If $T_{cd} < \frac{t_p \cdot N}{n}$, the laying machine is idle, i.e., paver, in anticipation of the requirements for loading dump trucks. In this case, t_a is defined as follows:

$$t_a = T_{cd} - \frac{t_p \cdot N}{n} \quad (6)$$

At $T_{cd} < \frac{t_p \cdot N}{n}$, dump trucks are idle, waiting for unloading t_{dt}.

$$t_{dt} = \frac{t_p \cdot N}{n} - T_{cd} \quad (7)$$

3. According to the formula (2), the performance of the asphalt paving and transport kit is determined.

4. According to formula (1), the cost of transporting and laying 1 m^3 of asphalt concrete mixture (other building materials) is determined.

5. Calculations of productivity P_e and cost of transportation of 1 m^3 of asphalt mix C_e are made for 2…10 arbitrary values N_i.

6. Dependence graphs $C_e = \varphi \cdot (N_i)$ and $P_e = \varphi \cdot (N_i)$ are constructed based on the calculation results.

7. According to the constructed schedule $C_e = \varphi \cdot (N_i)$, the minimum value C_e and the number of dump trucks 3 corresponding to this value are determined.

3 Results and discussion

The time spent on dump truck one trip T_{cd}, excluding loading time, is determined by the formula (4):

$$T_{cd} = 2\frac{L}{V_c} + t_u = 2\frac{17}{55} + 0{,}05 = 0.668 \text{ h.}$$

Further, considering the duration of one cycle of operation of vehicles T_{cd}, we determine the downtime of the WIRTGEN SUPER 1800 t_a asphalt paver using formula (6), as well as the downtime of the MAN TGL 26.280 t_{dt} dump truck using formula (7), and enter the calculation results in Table 2.

We consider examples of calculations of downtime of machines included in asphalt-laying and transport machines t_a and t_{dt} according to the ratio, respectively (6) and (7).

$$\text{At } N = 2 \; t_a = T_{cd} - \frac{t_p \cdot N}{n} = 0.668 - \frac{0{,}16 \cdot 2}{1} = 0.348$$

$$\text{At } N = 3 \; t_a = T_{cd} - \frac{t_p \cdot N}{n} = 0.668 - \frac{0{,}16 \cdot 3}{1} = 0.188$$

$$\text{At } N = 4 \; t_a = T_{cd} - \frac{t_p \cdot N}{n} = 0.668 - \frac{0{,}16 \cdot 4}{1} = 0.028$$

Further calculations t_a with $N_i < 4$ give negative values, which means that the downtimes of the WIRTGEN SUPER 1800 paver are eliminated, and vehicle downtimes begin, i.e., dump truck MAN TGL 26. 280, waiting for vehicles for unloading is formed; in other words, downtime of the dump truck t_{dt} begins.

We consider examples of calculating the downtime of a dump truck during the loading t_{dt} according to the formula (7).

$$\text{At } N = 5 \; t_{dt} = \frac{t_p \cdot N}{n} - T_{cd} = \frac{0,16 \cdot 5}{1} - 0.668 = 0.132$$

$$\text{At } N = 6 \; t_{dt} = \frac{t_p \cdot N}{n} - T_{cd} = \frac{0,16 \cdot 6}{1} - 0.668 = 0.292$$

Similarly, the downtime of a dump truck t_{dt} at N_i is calculated, and the results of the calculations are entered in Table 2.

Considering the obtained values of the downtime of the machines included in the asphalt-laying and transport machines t_a and t_{dt}. Then we determine the performance of the asphalt-laying and transport set and the cost of unloading and laying the set of machines according to the ratios, respectively (1). The results of the timing of determining the duration of laying asphalt mix T_{cd} for one loading are presented in Table 2.

To provide performance calculations P_e and cost C_e of the operation of asphalt paving and transport machines, we will transform considering several parameters of relations (1) and (2), and we will obtain the following:

$$P_e = \frac{G \cdot K_t \cdot K_{or} \cdot K_{fc}}{\gamma \cdot (T_{ca} + t_a)} = \frac{16.0 \cdot 0.83 \cdot 0.94 \cdot 0.95}{1,8 \cdot (0.023 + t_a)} = \frac{11,86}{1,8 \cdot (0.023 + t_a)} = \frac{6,59}{0.023 + t_a}$$

we get after transformation:

$$\boldsymbol{P_e = \frac{6,59}{0,023 + t_a}} \qquad (8).$$

Some calculations were made to determine the performance of the asphalt paving and transport kit P_e at different values of t_a, and the results of the calculation are entered in Table 2.

$$\text{At } N = 2 \; P_e = \frac{6,59}{0.023 + t_a} = \frac{6.59}{0.023 + 0.348} = 17.76 \text{ m}^3/\text{h}$$

$$\text{At } N = 3 \; P_e = \frac{6,59}{0.023 + t_a} = \frac{6.59}{0.023 + 0.188} = 31.23 \text{ m}^3/\text{h}$$

$$\text{At } N = 4 \; P_e = \frac{6,59}{0.023 + t_a} = \frac{6,59}{0.023 + 0,028} = 129.2 \text{ m}^3/\text{h}$$

$$\text{At } N = 5 \; P_e = \frac{6,59}{0.023 + t_a} = \frac{6,59}{0.023 + 0} = 286.52 \text{ m}^3/\text{h}$$

Further calculation P_e is inexpedient because at $N_i > 4$, the downtime of the paver is eliminated, and therefore the productivity of P_e = const is P_e = 286.52 m^3/h.

Table 1. The results of the timing of determining the duration of laying asphalt concrete mix T_{cd} per loading

№	Laying length l, m	Mix laying time t, sec	Mixture laying speed V_w, m/s	Mix laying time t, sec	Average laying time of the mixture t_{av}, hour
1	35	83	0.422	0.023	0.023
2		85	0.412	0.0236	
3		81	0.432	0.0225	
4		86	0.410	0.0239	
5		82	0.427	0.0228	
6		85	0.412	0.0236	
7		83	0.422	0.023	
8		86	0.410	0.0239	
9		81	0.432	0.0225	
10		85	0.412	0.0236	
11		81	0.432	0.0225	
12		83	0.422	0.0.23	
13		80	0.437	0.0222	
14		87	0.402	0.0242	
15		84	0.417	0.0233	
16		80	0.437	0.0222	
17		83	0.422	0.023	
18		79	0.443	0.0219	

Now let's start calculating the cost of loading and unloading operations C_e, for the transportation and laying of asphalt concrete mixture of 1 m^3 according to the formula (1).

To facilitate the calculation of values C_e for different t_a, it transforms formula (1), and we get:

$$C_e = \frac{\gamma}{2 \cdot G \cdot K_{uf} K_{fc}} \cdot [C_{m-h.dt}(T_{cd} + t_{dt}) + 2 \cdot G \cdot L] + \frac{C_{m-h.dt}}{P_e} + W_p + C_{ac} =$$

$$= \frac{1{,}80}{2 \cdot 16{,}0 \cdot 1 \cdot 0{,}95} \cdot [9600 \cdot (0.668 + t_{dt}) + 2 \cdot 450 \cdot 17] + \frac{9200}{P_e} + 980 + 11640 =$$

$$= 13901.1 + 566.4 \cdot t_{dt} + \frac{9200}{P_e}$$

Thus, we obtain the ratios for calculating the cost of work

$$C_e = 13901.1 + 566.4 \cdot t_{dt} + \frac{9200}{P_e} \quad (9)$$

The optimal number of vehicles in a set of machines should ensure the maximum performance of the set at the minimum cost of transportation and lay of the asphalt mix. This problem is solved by a graphical-analytical research method. An algorithm for optimizing the performance of asphalt paving and transport machines was developed, shown in Fig. 1.

Next, we calculate the cost of the work of asphalt paving and transport machines for different N_i:

At $N = 2$

$$C_e = 13901.1 + 566.4 \cdot t_{dt} + \frac{9200}{P_e} = 13901.1 + 566.4 \cdot 0 + \frac{9200}{17.76} = 14419.1 \text{ sum/m}^3$$

At $N = 3$

$$C_e = 13901.1 + 566.4 \cdot t_{dt} + \frac{9200}{P_e} = 13901.1 + 566.4 \cdot 0 + \frac{9200}{31.23} = 14195.7 \text{ sum/m}^3$$

At $N = 4$

$$C_e = 13901.1 + 566.4 \cdot t_{dt} + \frac{9200}{P_e} = 13901.1 + 566.4 \cdot 0 + \frac{9200}{129,2} = 13972.3 \text{ sum/m}^3$$

At $N = 5$

$$C_e = 13901.1 + 566.4 \cdot t_{dt} + \frac{9200}{P_e} = 13901.1 + 566.4 \cdot 0 + \frac{9200}{286.52} = 14007.9 \text{ sum/m}^3$$

Similarly, we calculate the cost C_e of a set of machines for different values of N_i , and enter the results of the calculations in Table 2.

Table 2. The results of calculating the indicators of the asphalt-laying and transport set of machines

№	Number of dump trucks	Operating performance set of machines	Duration of asphalt paver downtime	Duration of dump truck downtime	Cost of transportation of materials
	N_i	P_e, m^3/h	t_a, h	t_{dt}, h	C_e, sum/m^3
1	2	17.76	0.348	0	14419.1
2	3	31.23	0.188	0	14195.7
3	4	129.2	0.028	0	13972.3
4	5	286.52	0	0.132	14007.9
5	6	286.52	0	0.292	14038.6
6	7	286.52	0	0.452	14119.2
7	8	286.52	0	0.612	14279.8
8	9	286.52	0	0.772	14370.5
9	10	286.52	0	0.932	14461.1

Thus, according to the results of the experimental study of this work, which are presented in Table 2., we draw up graphs of the dependence according to the formula (3):

$$P_e = f(N_i) \text{ and } C_e = f(N_i)$$

The graph of the dependence of the performance of a set of machines on the number of dump truck MAN TGL 26. 280 is shown in Fig. 2.

The analysis of the dependency graph $P_e = f(N_i)$ shows that the performance of the asphalt paver and transport kit, as well as the operational performance of the asphalt paver, depending on the number of vehicles, varies significantly.

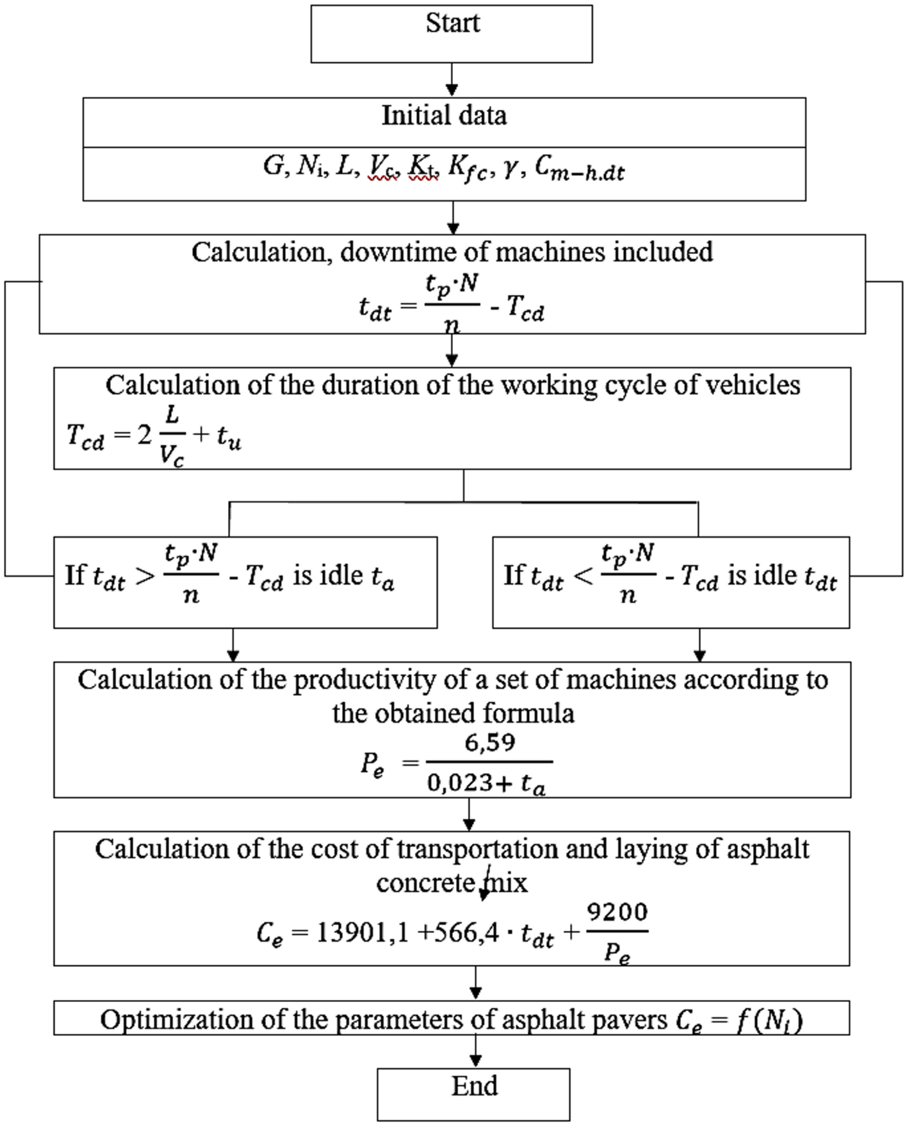

Fig. 1. Algorithm block diagram for optimizing indicators asphalt paving machines.

From the graph (fig. 2.), it can be seen that the performance of the paver sharply increases to $N = 5$. With an increase in Ni > 5, the performance of the WIRTGEN SUPER 1800 paver remains unchanged, i.e., Pe = const this is explained by the fact that during the operation of machines in the asphalt paving and transport set, the downtime of the main machine of the WIRTGEN SUPER 1800 ta asphalt paver is minimized. A further increase in the number of vehicles N_i only leads to an increase in the downtime of vehicles t_{dt}, i.e., dump truck.

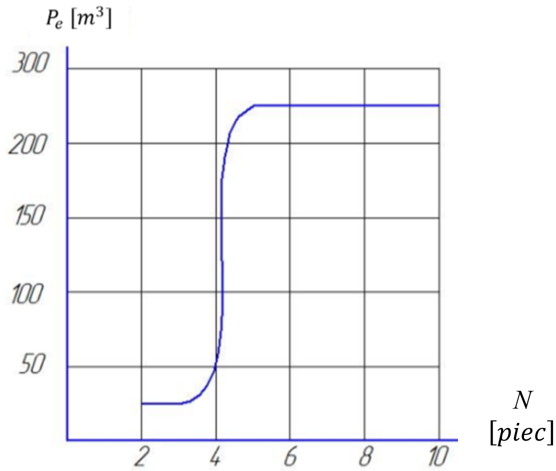

Fig. 2. Graph of dependence of the performance of a set of machines on the number of dump trucks MAN TGL 26.280.

Next, we draw up a graph of the dependence of transportation and transportation costs and laying the asphalt mix on the number of dump trucks of the MAN TGL 26.280 brand in the asphalt paving and transport kit, which is shown in Fig. 3.

From the dependency graph in Fig. 3, $C_e = f(N_i)$ it can be seen that the optimal value of the number of vehicles in the set is $N_{opt} = 4$.

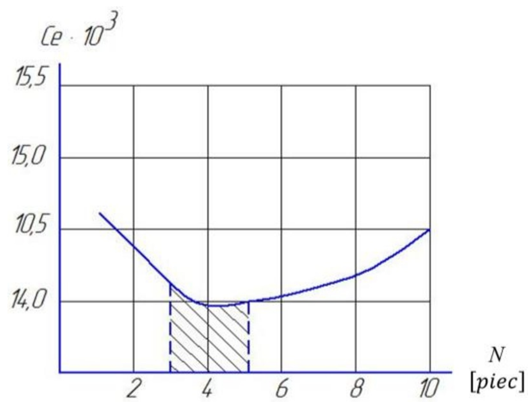

Fig. 3. Graph of the dependence of the cost of loading and transporting the asphalt mix on the number of dump trucks MAN TGL 26.280 in the asphalt paving and transport set.

However, a decrease in the number of vehicles below $N < 4$ leads to a sharp increase in the cost of asphalt paving and transport machines, as well as a decrease in the performance of the paver; this circumstance is associated with an increase in the downtime of the paver, i.e., WIRTGEN SUPER 1800 asphalt paver.

4 Conclusion

The obtained results of the study, the developed methodology for determining and calculating the effective use of asphalt paving and transport machines by optimizing the performance of a set of machines, can be used in a road construction and repair enterprise, where asphalt paving and transport machines are widely used.

The developed algorithm block diagram for optimizing the performance of a set of asphalt paving and transport machines is also used in industry enterprises where these machines are operated.

As a result of the study, a methodology has been developed for determining and calculating the effective use of asphalt paving and transport machines; an algorithm for the flowchart of optimization of the parameters of asphalt-laying and transport machines has been developed.

Thus, the number of MAN TGL 26.280 dump trucks, optimal for the operating conditions of the asphalt paving and transport set, necessary for the uninterrupted operation of the set, should be within, and these circumstances lead to an increase in the efficiency of the use of the asphalt paving and transport set of machines.

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