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SIMULATION FOR SELECTING ROAD WORKS EQUIPMENT

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Abstract. Efficiency of road works is conditioned by selection of machines and synchronizing their operations. Modelling these works using queuing theory allows the planner to conduct an in-depth analysis of the system's operation to find the best machine types and their optimal number. For simple cases, analytic formulas are used to calculate such parameters as a probability of a server's standing idle, average length of a queue, or average waiting time. However, complex real-life systems are to be analyzed more efficiently by means of simulations. The paper presents simulation model of a road repaving project. Using it, the authors evaluated the economic effect and output of the system served by different machine sets. Applying a number of additional optimization criteria (cost, productivity, machine utilization rates, etc.) the authors were able to find most suitable machine sets.

Keywords: roadwork planning, repaving, queuing model, simulation, CYCLONE, optimization.

1. Introduction

Solving practical problems of business operations and selecting best options is a complex task – even if the decision environment is treated as deterministic. The methods of supporting the decision making process are numerous, they develop continuously and find many applications (Keršulienė, Turskis 2011; Stanujkic *et al.* 2012).

From the point of decision making, construction may be considered an especially challenging branch of industry as, regardless of country, technology level or economic conditions, it is prone to considerable operational risk (Ghoddousi, Hosseini 2012). Thus, the assumption of deterministic character of construction projects may lead to wrong decisions, and many researchers propose tools or methodologies aimed to improve construction planning. For instance, Paslawski (2011) puts forward that flexibility is needed to manage construction risks successfully and prompts adjusting to dynamically changing environment by preparation of alternative solutions. Jaskowski and Sobotka (2012) argue that, in the scheduling process, it is possible to form new performance variants by changing activity precedence logic in a way that leads to minimizing the project duration without exceeding the allowed budget. Jaskowski and Biruk (2011) propose a different method of improving the construction planning reliability: the method bases on the idea of schedule buffer allocation; proper buffer sizing is claimed to reduce negative effects of random conditions occurring as the project progresses, and improve efficiency of project activities. Some of the researchers model uncertainty using fuzzy logic (Han, Liu 2011; Keršulienė, Turskis 2011) or interval grey numbers (Stanujkic 2012; Zolfani *et al.* 2012).

However, for optimization of complex management processes the stochastic simulation is recommended and used by many researches, especially in combination with optimization algorithms (Biruk, Jaskowski 2008; Jaskowski, Biruk 2011; Napalkova, Merkuryeva 2012).

Many construction processes are of cyclic nature, with operations repeated in the same sequence that results from method of their execution. Duration of such repeated operations is usually a little different in each cycle. This is due to a variety of factors affecting productivity of the resources and changing conditions of work. Thus, cyclic construction processes are stochastic, possible to be modeled as queuing systems, and examined by means of simulations or tools of statistical analysis. The results of such analyzes are the basis for planning the works with respect to composition of machine sets or worker crews,

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estimating process time, and harmonizing the work. Simple queuing systems have been described by analytical formulas that concern mean utilization rates of servers, mean waiting time, mean service time, probability of a certain number of arrivals to the system, etc. However, real-life systems are complex (a number of servers processing customers in sequence, in parallel, in a mixed manner; a number of queue with different serving disciplines; a number of customer types) and take form of queuing networks. If the systems actually operate, information on their performance is possible to be collected on site and analyzed by means of statistical methods. In the case of systems at the planning stage, computer simulations provide input for the analysis.

2. Computer simulations of queuing networks

Simulation is a technique used to imitate operation of a real-life system by means of a dynamic model. In the case of computer simulation, the real-life system is modeled by means of a computer program. Depending on the character of the model's state variables, simulation methods are continuous (if the state transition is of continuous character), discrete (discrete event simulations), or hybrid. Continuous simulations are rarely used for the analysis of queuing networks (Roy, Mohopatra 1993). The literature on the subject recommends discrete simulation to analyzing complex systems (Özgün, Barlas 2009).

Before simulation tests are conducted, a model of the real-life system has to be built. There are three basic modeling strategies for defining the concept of model analysis and the way of its creation (Abduh *et al.* 2010). These are:

– process interaction (PI) strategy that focuses on transaction flows inside the systems,
– activity scanning (AS) strategy that identifies processes and conditions required for their complection, and
– event scheduled strategy (ES) based on modelling events that are likely to occur or whose occurrence has been planned.

In practice, these strategies are used in combinations. In the case of construction processes, a combination of AS and ES strategies is recommended, and referred to as the three-phase activity scanning method.

It was the basis for the Halpin's CYCLONE method of modelling cyclic construction operations (Halpin 1977). Here, the graphic model of a system uses only 5 elements (Table 1). Resources (units) are moved between network elements along the arcs according to the system's logic. Unit flows are held in a queue (to be served or to start work) and in the "normal activity" or "COMBI activity" elements (for the time of conducting processes), and then they are forwarded to the next elements (by being duplicated). The "counter" block enables the user to count the number of cycles and units of output. The "function" block allows for consolidation of resources (turning them into products). It is possible to connect normal activities, COMBI activities, and "function" blocks by probabilistic arcs – this facilitates modeling of optional processes of certain probability of occurrence.

CYCLONE has found application in a number of computer simulators designed for analysis of construction processes. Some of them are MicroCYCLONE, DISCO, PROSIDIC, INSIGHT, RESQUE, STROBOSCOPE, SIMPHONY, WebCYCLONE, COOPS, UM-CYCLONE, COMSim. The CYCLONE modeling approach was also implemented in the COST (Construction Operations Simulation Tool) by Cheng *et al.* (2000), that allows the user to model activity times as fuzzy numbers. Cheng and Feng (2003) integrated CYCLONE simulation with a genetic algorithm to facilitate finding optimal resource combinations.

Abduh *et al.* (2010) argue that the main practical problems of using simulations for analyzing construction processes are related with limited access to input (lack of statistical data on construction activities' times with respect to distribution types and parameters), lack of modeling expertise (the existing software requires from the user much more than basic computer skills, sometimes the user has to translate a graphic model into a computer program, the simulation reports have to be interpreted), and software accessibility (costly licenses). Construction practitioners prefer widely available software and universal systems facilitating calculations (like spreadsheets) to single-purpose specialized systems, regardless of their commercial or in-house origin.

The authors used WebCYCLONE (Halpin *et al.* 2003) as a simulation toll was used. The tool is available free of

Table 1. Graphic symbols used in CYCLONE (Halpin 1977)

Name	Symbol	Description
Normal activity		A resource is being processed without waiting in the line, or the resource is engaged for the time of conducting the activity and then released. Within the block, a number of activities may run in parallel.
COMBI activity		The activity starts if resources are available (i.e. there are units waiting to be served) in all preceding queues. Within the block, a number of activities may run in parallel.
Queuing node		A place where resources wait to be served by COMBI blocks.
Consolidated function node		Consolidating resources into e.g. products
Counter		Counting output units, measuring flows.
Arc		Represent network logic, the sequence of resource flows through the system.

charge from the website https://tomcat.itap.purdue.edu/WebCYCLONE/Cyclone.jsp. Calculations are possible to conducted by means of other software, e.g. EZStrobe (downloadable from http://www.ezstrobe.com/), which requires that the model is created graphically with limited analytic description (e.g. activity times data) (Martinez 2001).

3. Example

The object of analysis is a road resurfacing project in Netherlands. Its location, and location of asphalt plants providing the material, is presented in Fig. 1. The resurfacing process comprised the following operations: milling the old wearing course, transporting the reclaimed material to a stacking area, transporting asphalt mix to the construction site, and placing new wearing course.

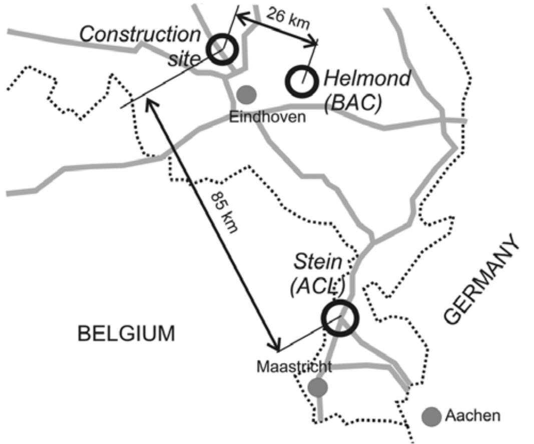

Fig. 1. Location of the project and asphalt plants

Milling the old wearing course was planned to be done by means of three milling machines. Reclaimed material was loaded into trucks and transported to a stacking area at the Brabantse Asfalt Centrale in Helmond (BAC) asphalt plant that was also the basic supplier of asphalt mix for the project. Considering the limited number of scales available at the plant, only 2 trucks were possible to be unloaded at a time.

Two suppliers of asphalt mix were available:

- the main was BAC, with a mean capacity of 240 Mg of mix/h;
- an auxiliary plant, Asfalt Centrale Limburg in Stein (ACL), with a mean capacity of 130 Mg/h.

Placing new wearing course was planned to be conducted by 2 pavers that covered half of the lane width at one run. Both the asphalt mix and reclaimed material were to be transported by 4-axle trucks. To avoid traffic problems, the rate of placing the new wearing course was to be close to the rate of milling. This was an underlying assumption with regard to the selection of milling machines and pavers type (capacity) and number.

Fig. 2 presents a CYCLONE model of this resurfacing process – usual in the practice of such projects. Table 2 lists the input data – durations of activities, including

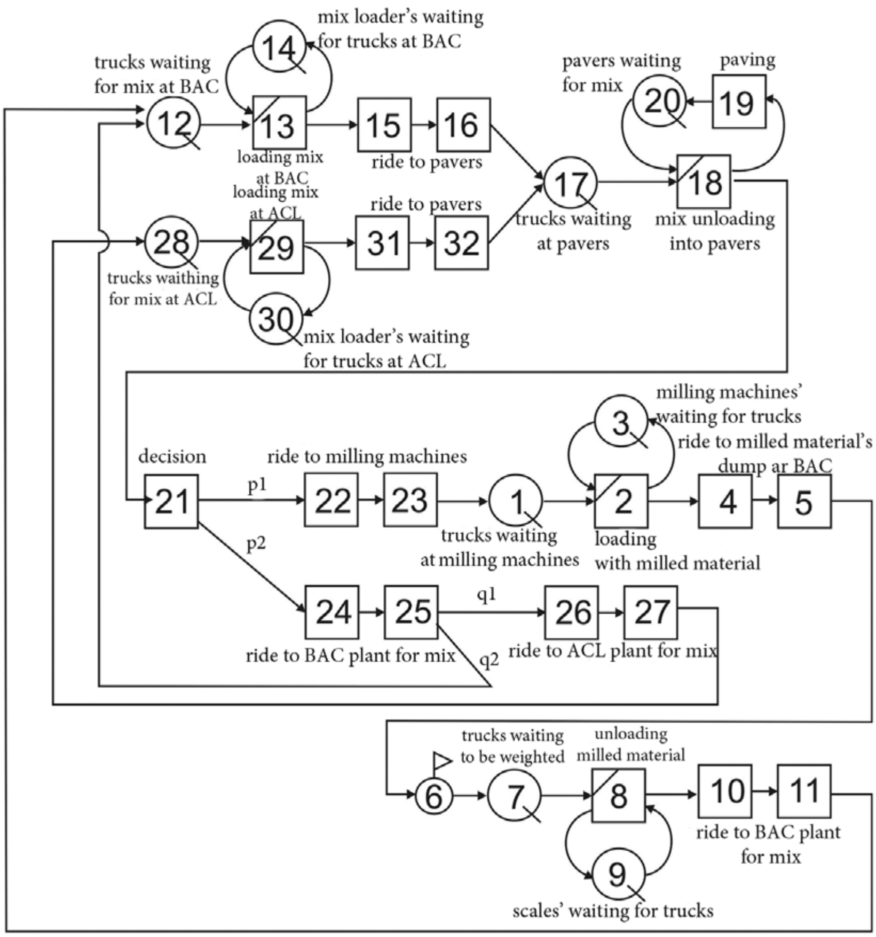

Fig. 2. CYCLONE network – model of repaving process for the example case

Table 2. Activity duration data for the example case

Symbol	Activity	Duration type	Distribution	Parameters
2	Milling and loading reclaimed material	Probabilistic	Beta	15; 19; 2; 4
4	Transport of reclaimed material to BAC	Deterministic (shift)	–	28
5	Transport of reclaimed material to BAC	Probabilistic	Exponential	5.28
8	Unloading the reclaimed material	Probabilistic	Beta	5; 8; 2; 4
10	Truck relocation to mixture loading at BAC	Deterministic (shift)	–	3
11	Relocation to mixture loading at BAC	Probabilistic	Exponential	2
13	Mix loading at BAC	Probabilistic	Beta	3; 6; 2; 4
15	Mix transport from BAC to the site	Deterministic (shift)	–	32
16	Mix transport from BAC to the site	Probabilistic	Exponential	5.28
18	Unloading into pavers' containers	Probabilistic	Beta	8.5; 10.5; 2; 4
19	Paving	Probabilistic	Beta	11; 14; 2; 4
21	Decision	Deterministic	–	0
22	Truck relocation to milling area	Deterministic (shift)	–	2
23	Truck relocation to milling area	Probabilistic	Exponential	1
24	Empty return to BAC	Deterministic (shift)	–	28
25	Empty return to BAC	Probabilistic	Exponential	5.28
26	Empty return to ACL	Deterministic (shift)	–	37
27	Empty return to ACL	Probabilistic	Exponential	5.17
29	Mix loading at ACL	Probabilistic	Beta	3; 6; 2; 4
31	Mix transport from ACL to the site	Deterministic (shift)	–	72
32	Mix transport from ACL to the site	Probabilistic	Exponential	7.5

distribution type and parameters of probabilistic values. Input for the analysis was collected during observation of works performed in the past and executed in similar conditions. Some durations were assumed to be deterministic, and they are expressed by one value, in minutes. The value characterizing an activity of exponential distribution is the mean reduced by the shift of the waiting time distribution, and is also given in minutes. In the case of beta distribution, the values are maximum duration, minimum duration, and shape parameters, in minutes. The truck ride times include time for maneuvers at the destination points and organization-related activities, such as answering to calls and document handling. The rides are modeled by two blocks because this was necessary to allow for their being of shifted exponential distribution. The unit cost of machines (wet with driver), based on information from the market, were assumed as follows: for trucks 30 EUR/h, for pavers – 50 EUR/h, for milling machines – 90EUR/h.

The repaving process was simulated to run for ten 8-hour working shifts. The aim of simulation was to find the number of trucks to serve the process, and frequencies (probabilities) of the trucks' selecting optional routes:

– after dumping the mix into loaders (decision node 21: $p1$ is the frequency of trucks' heading for collection of reclaimed material, and $p2$ is the frequency of the tricks' going to BAC asphalt plant to fetch asphalt mix, $p2 = 1 - p1$);

– after arriving at BAC plant (node 25: $q1$ is the frequency of the truck's going to ACL plant, and $q2$ – waiting at BAC to be loaded, $q2 = 1 - q1$).

During simulation, the milling machines' and pavers' utilization rates were checked: they are required to be similar, with minimum idle time, to assure uniform rate of work and low cost. Similarly, the number of trucks loaded at asphalt plants was checked to assure that the plant's capacity was not exceeded: it was assumed that the average load of a truck was 26.5 Mg, so the BAC plant would not be able to load more than 724 trucks, and the ACL plant – 392 trucks during 10 days of work.

The 1st stage of simulations consisted of analyzing the effect of probabilities $p1$ and $q1$ on the milling machines' and pavers' capacity utilization level, in this case measured by the mean waiting time (so the mean time of pavers' or milling machines' waiting before being served by a truck).

Table 3 lists simulation results for the assumed number of trucks in the system (10 trucks). Changing the number of trucks is not expected to affect the proportion between the milling machines' and pavers' capacity utilization levels. The results indicate that milling machines had long idle times. The lowest mean idle time for milling machines was obtained for $p1 = 1$, so in the case that deliveries come only from the main asphalt plant (BAC), and the trucks move to serve the milling process immediately after unloading asphalt mix.

The next stage of analysis was devoted to finding ways of reducing idle time of milling machines and pavers – and checking if there are grounds for increasing the number of trucks in the system, which inevitably increases cost of transport. Table 4 lists the results of simulations for different numbers of trucks. The lowest cost of machine set per truck loaded with milled material (so the unit production cost in the leading process) was obtained for 12 trucks in the set, but in this case the milling machines had quite a lot of idle time. This reduces the speed of repaving works.

Therefore, the 3rd stage of analysis considered the grounds for changes to the organization of works by excluding one asphalt plant (ACL) and allowing the trucks to move from the pavers directly to the milling machines. It was assumed that the travel time between stacking area at BAC and the milling area is a random variable of exponential distribution, mean value of 5.28 min and a shift of

Table 3. Simulation results – first stage (data for ten 8-hour shifts, 10 trucks in the system)

$p1$	$q1$	Number of truckloads filled by milling machines	Mean time of milling machines' waiting for trucks, min	Number of truckloads of mix delivered to pavers	Mean time of pavers' waiting for mix delivery, min	Number of mix truckloads filled at BAC plant	Number of mix truckloads filled at ACL plant
0.2	0.2	75	162.3	317	9.1	130	196
0.2	0.4	79	156.2	347	6.5	187	165
0.2	0.6	90	133.5	385	3.8	272	117
0.2	0.8	97	127.4	415	2.0	360	59
0.4	0.2	142	82.8	334	7.6	183	156
0.4	0.4	153	75.8	355	6.0	231	127
0.4	0.6	167	68.6	383	3.9	300	88
0.4	0.8	174	64.3	408	2.4	369	45
0.6	0.2	225	46.7	357	5.8	256	107
0.6	0.4	233	44.4	369	4.9	291	84
0.6	0.6	240	43.0	383	4.0	327	62
0.6	0.8	251	40.3	403	2.7	376	31
0.8	0.2	311	29.6	373	4.6	327	51
0.8	0.4	320	28.3	386	3.8	353	37
0.8	0.6	325	27.6	393	3.3	371	26
0.8	0.8	332	26.7	400	2.9	390	14
1	0	397	19.6	389	3.5	395	0

Table 4. Simulation results – second stage, according to number of trucks in the system (ten 8-hour shifts, at p1 = 1 and q1 = 0)

Number of trucks in the system	Number of truckloads filled by milling machines	Mean time of milling machines' waiting for trucks, min	Machine set cost per truckload of milled material, EUR	Number of truckloads of mix delivered to pavers	Mean time of pavers' waiting for mix delivery, min	Number of mix truckloads filled at BAC plant
5	210	50.8	198.10	207	24.9	209
6	250	40.4	176.00	246	17.8	248
7	291	32.6	159.45	285	12.5	289
8	328	27.2	148.78	322	8.7	324
9	365	22.8	140.27	358	5.8	362
10	397	19.6	135.01	389	3.5	395
11	426	17.2	131.46	417	1.9	422
12	449	15.5	130.07	439	0.8	445
13	456	15.1	133.33	445	0.5	450
14	457	15.0	138.29	445	0.5	452
15	458	15.0	143.23	445	0.5	452

32 min. A CYCLONE network representing the modified repaving organization is shown in Fig. 3.

Table 5 lists simulation results for different values of probability $r1$ ($r2 = 1 - r1$) of selecting an option of going directly from the BAC's reclaimed material stacking area to the milling area, instead of taking the asphalt mix and going to the pavers. This simulation was conducted for 13 trucks (the number of trucks is not expected to affect the proportion between capacity utilization levels of milling machines and pavers). The results indicate that at the probability $r1 = 0.57$ corresponds to the lowest mean idle time of milling machines and pavers due to waiting for trucks.

Table 6 presents the results for different numbers of available trucks. The lowest cost of the machine set per truck loaded with reclaimed material is obtained in the case of 18 trucks employed to serve the process; moreover, it is with a satisfactory level of milling machines' and pavers' capacity utilization. So in the analyzed case, a set of 18 trucks cooperating with 2 pavers, 3 milling machines and 1 asphalt plant provides lowest cost of repaving, as the speed of milling and paving is similar. The repaving cost is by 23%

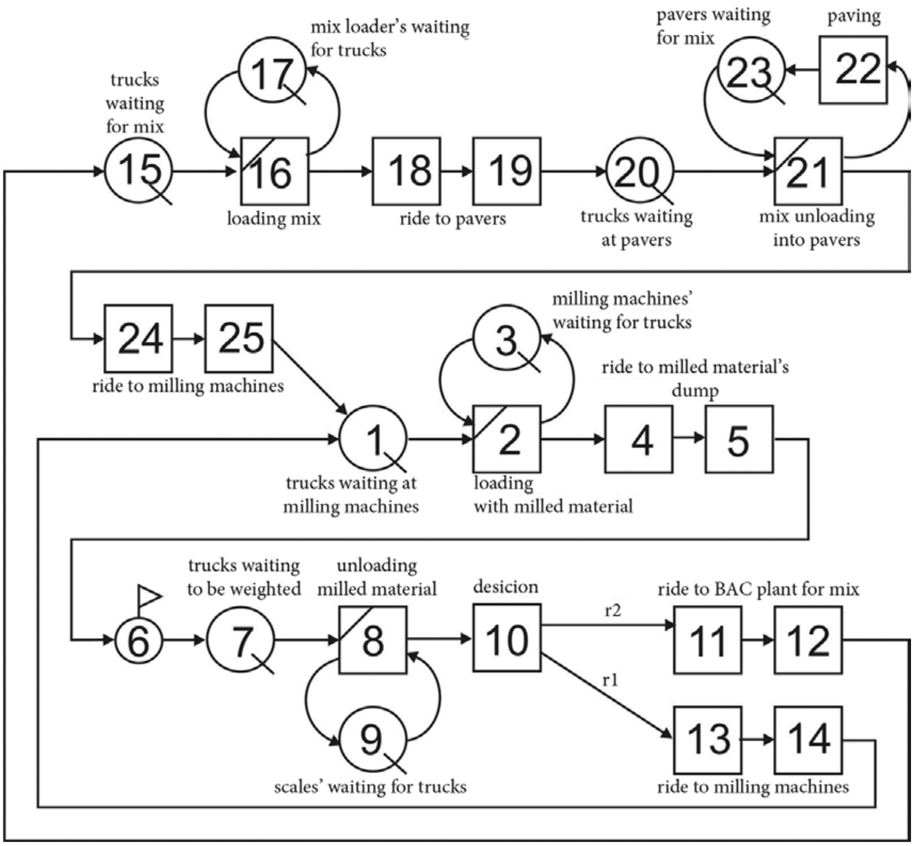

Fig. 3. CYCLONE network – model of repaving process for the example case with modified organization of works (3rd stage of analysis)

Table 5. Simulation results (simulation of ten 8-hour shifts, 13 trucks in the system)

$r1$	Number of truckloads filled by milling machines	Mean time of milling machines' waiting for trucks, min	Number of truckloads of mix delivered to paver's containers	Mean time of pavers' waiting for mix delivery, min	Number of mix truckloads filled at BAC plant
0.90	491	12.8	433	1.1	438
0.80	530	10.7	416	1.9	421
0.70	552	9.7	377	4.3	383
0.60	571	8.8	331	7.9	335
0.57	576	8.6	319	8.9	323
0.56	580	8.4	310	9.8	314
0.55	582	8.4	309	9.9	313
0.54	581	8.4	307	10.1	309
0.50	590	8.0	290	11.8	291
0.40	607	7.3	235	19.5	238

lower than in the basic case (analyzed in the 2nd stage of simulations), and the capacity utilization is better by 63%.

4. Conclusions

1. Machine sets for construction works need to be organized with care. Following the harmonization rule, the highest output is obtainable if parameters of the machines are adjusted, and their work is synchronized.

2. In the paper, the authors designed an optimal machine set for a repaving project, modeling construction processes according to CYCLONE method, and using widely accessible simulation software. The main criterion for optimization was assumed to be lowest unit production cost. The constraints were: assuring similar rate of processes running at the same time (milling and paving), and not exceeding the production and loading capacity of asphalt plants.

3. The optimal solution holds in certain circumstances – any change of conditions would require changing the model parameters and repeating calculations. Even very similar projects, conducted in a different location, would require a different configuration of the model.

4. Simulations allow the planner to find the best way of organizing the works. The example illustrates benefits of applying them to construction management and building-site logistics.

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Table 6. Simulation results for different numbers of trucks in the system (simulation of ten 8-hour shifts, at $r1 = 0.56$)

Number of trucks	Number of truckloads filled by milling machines	Mean time of milling machines' waiting for trucks, min	Machine set cost per truckload of milled material, EUR/truck-load	Number of truckloads of mix delivered to pavers	Mean time of pavers' waiting for mix delivery, min	Number of mix truckloads filled at BAC plant
10	453	15.2	118.32	249	17.2	252
11	498	12.4	112.45	273	13.9	273
12	539	10.3	108.35	296	11.3	297
13	576	8.6	105.56	319	8.9	323
14	611	7.2	103.44	343	6.9	348
15	646	5.9	101.55	366	5.1	369
16	674	5.0	100.89	382	4.0	388
17	705	4.1	99.86	399	3.0	402
18	730	3.3	99.73	411	2.2	417
19	753	2.8	99.87	423	1.6	426
20	772	2.3	100.52	430	1.2	433

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