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Analysis of the Construction Machinery Work Efficiency as a Factor of the Earthworks Sustainability

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Abstract. Being aware of the construction machinery work efficiency is one of the key conditions of dynamic planning of machine work at the construction site and it can be considered as one of the earthworks sustainability factors. The main topic of this paper is the time study analysis of one standard technological cyclic construction machine process (the excavators' loading the transportation vehicle), which was observed on-and-off site and analysed. On-site data was obtained by snapback chronometry method with the purpose of determining actual work efficiency; while the (off-site) planned work efficiency was determined using the standardized tables. The aim was to determine the existence of a deviation and examine the differences between planned and actual work efficiency of particular technological process in earthworks as well as to identify its cost-effective area as a prerequisite for identifying the earthworks sustainability. As the earthworks sustainability is the synthesis and concordance of beneficial activities for technological, economic, environmental and social performance context, the balance of excavators' work efficiency is needed. It was concluded that in order to achieve sustainability, i.e. to be in cost-effective area, the maximum value of excavators' cycle time extends up to 50 seconds.

1. Introduction

With the growing industrialization of construction works, the role of machinery on a construction site is vital for achieving productivity, working standards and performance of contractors. Present construction projects are highly mechanized and have been evolving continuously [1]. Adoption of mechanized practices accelerates execution of works on the construction site, thus shortening the time and cost of completing the project [2].

The choice of machinery for a specific construction site is mainly result of finding a solution that gives the greatest practical or planned achievement, i.e. work efficiency at the lowest cost. However, the increasingly popular phenomenon of sustainability in construction emphasizes the preservation of energy, efficiency, environment, economy and human well-being. In such context, selecting the most suitable machinery from the available options is highly demanding. Therefore, when selecting construction machinery, there is a need for the most diverse criteria that have a positive impact on operational efficiency, productivity, cost reduction, environment and human well-being [1].

The contractor does not always have an opportunity to select the optimal machine for the construction purpose but to perform work with the available machinery. Therefore, it is of crucial importance to calculate available machines' work efficiency in order to achieve the best possible result. Specifically, the efficiency is one of the key conditions of machines' work dynamic planning at the construction site resulting in cost-efficiency and desired productivity. Such overall consideration of various parameters results in work efficiency information that can be considered as one of the earthworks sustainability factors.

In order to examine the differences of planned and actual work efficiency, in this research on-site measurement of excavator work with snapback chronometry method was carried out. The aim of this paper is to determine the existence of a deviation between the work standards obtained by on-site measurement and that obtained through the calculation of standard cyclic construction machine by standardized tables. Based on the results obtained, it is necessary to identify the working conditions in which the machine performs the most productive and most cost-effective work, and in that sense partly contribute to the creation of sustainable working conditions of the observed excavator.

2. Research context and literature review

For reliable planning of both work costs and time, it is necessary to know the work efficiency of the machinery that is intended to be used, especially the efficiency in specific construction work conditions. The machine work efficiency can be defined as the amount of work with satisfactory quality, expressed in appropriate calculation units (m^3, m^2, m, pcs, t) which takes place in a unit of time, usually one hour [3]. The machine's theoretical work efficiency is the maximum efficiency of the machine and can be measured on the basis of machine operation without loss of time and failure, under optimum conditions. The practical or planned work efficiency of the machine, on the other hand, tries to more precisely determine the value of the real work efficiency, and it takes into account work-related failures due to the technology itself, the machine mode and the person who manages it [4]. These site conditions are entered in the form of reduction coefficients in the calculation of the practical efficiency.

Determining the actual work efficiency of standard construction machinery is one of the key preconditions for dynamic planning of construction site work. That is why methods of calculating the work efficiency of construction machinery are often subject to research in the field of organization and construction technology and are also a special subject of interest of manufacturers of construction machinery [5].

Another very important element in the planning of machinery work which is directly related to the machine's work efficiency, is the determination of the machine work cost, which is mainly expressed in unit costs [6]. Unit labour costs are direct costs and are calculated in the unit price analysis as multiplication of the cost of a particular machine (how much it costs the contractors) and time standards which should be the size inversely proportional to the average efficiency achieved [3].

For construction practice, not knowing the work efficiency needed to plan costs and time is a common problem, i.e. lack of appropriate standards, therefore Vidaković et al. [3] suggest that each construction company should create its own internal standards for the work being performed and the machines they use to have relevant data to calculate their work efficiency. The development of these standards should imply the real work efficiency that machines have achieved on the construction site in real time period. They are best obtained by measuring machine operation, either by chronometry method or some more sophisticated methods such as advanced wireless technology (such as GPS, RFID, sensors, lasers, etc.) [7–8]. Car-Pušić et al. [5] determined the existence of differences between the work efficiency obtained at the planning stage and those obtained by on-site measurements and showed that the problem stems from the standard coefficient values [9–12] associated with organizational conditions. Further research [13–14], in which the chronometry method was applied, confirmed that the measured work efficiency of the machinery, in relation to the planned work efficiency, was higher by 30%. The research [15] confirmed the existence of differences between planned and actual work efficiency and emphasized the need for further study of machine work. This is of particular importance if the aspects of sustainability are taken into account. As a matter of fact, sustainability can be seen from the point of view of the working process, or from the point of view of the nature preservation.

3. Methodology

3.1. Prerequisites for achieving earthworks sustainability

Successful realization of earthworks in terms of sustainability is reflected in the ability to reach balance between optimized and efficient planning and performing, profitable actions, while preserving nature and with long-term effects of all results and resources. The optimization and efficiency of planning and performing earthworks is the application of best practices, standards and technology with the criteria of cost-efficiency, availability of machines and safety. In relation to the planned project, it is necessary to select the machine with optimal power and appropriate tool size. Also, it is important to reduce unnecessary amount of work, use of means for work and energy consumption. The long-term effects in results mean the fulfilment of a high quality project with the nature conservation criterion and the lowest level of air, water and soil pollution.

Considering the long-term effects, an important segment is the mechanical state of the machines, their age and maintenance regularity. Scheduled and regular maintenance of machines reduces the possibility of sudden, unexpected failures that cause delays and losses on the construction site. In addition, machine failures can result in unfavourable and adverse conditions of the environment. Tracking and monitoring the earthworks operations enable correct decision-making, implementation of improvements, more accurate predictions of activity duration, necessary costs and resources as well as early detection of defects in order to take timely implementation of appropriate corrective measures. Profitable actions represent operations and activity that contribute to the preservation and promotion of the welfare of the whole community and environment. Also, it is important to encourage motivated working environment with focus on solutions. Sustainability of earthworks is the synthesis and concordance of beneficial activities for technological, economic, environmental and social performance context (Figure 1). Sustainable project results of earthworks are duration and exploitation of goods for the long-term period. Responsible realization of earthworks meets the needs and ensures progress without compromising future activities.

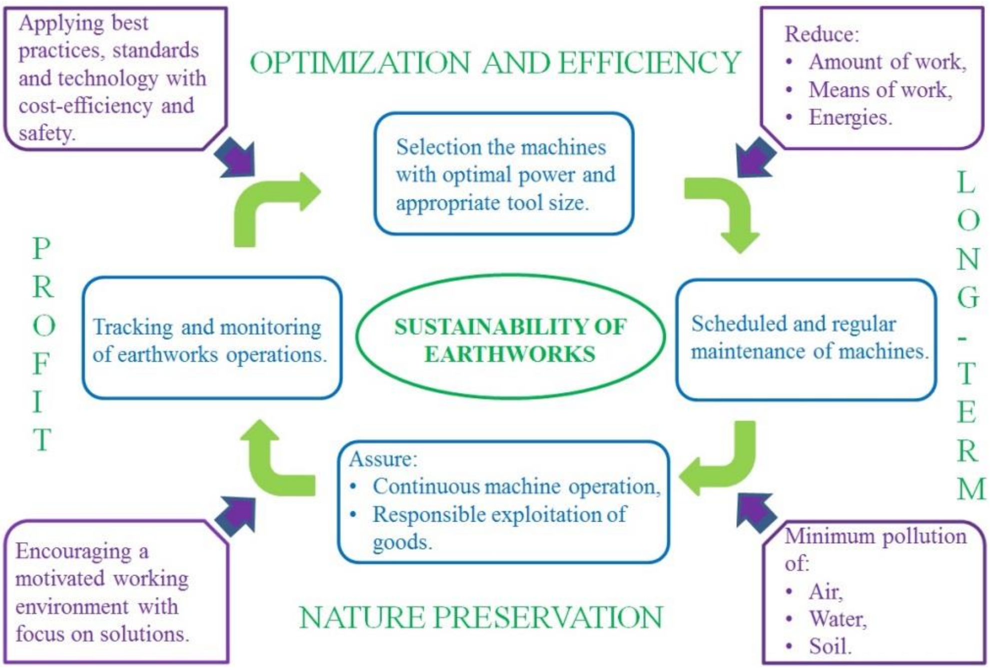

Figure 1. Balance in conditions for earthworks sustainability.

One particular technological process of earthworks is loading materials from excavation into transportation vehicles. In order to effectively perform the work, it is especially important to dimension the machinery to enable continuous operation of the machines which load material, such as excavator or wheel loaders, ensure sufficient number of transportation vehicles, such as a tipper truck or a dump truck. Measuring actual work efficiency of the construction machinery represents an aspect of the tracking and monitoring of operations as a part of earthworks sustainability.

3.2. Methodology proposal

The methodology proposal for tracking and monitoring of earthworks operations consists of theoretical preparation, selection of an appropriate tracking tool, field research, comparative analysis and conclusions (Figure 2). Theoretical preparation involves defining a key machine, or machines for the technological process of earthworks and calculation of their planned work efficiency on assumed conditions of the construction site. Field research involves tracking and monitoring the machine for the purpose of measuring its actual work efficiency during the operations at the construction site. The essential link between theoretical preparation and field research is the selection of an appropriate tool for tracking the machine without disrupting its normal work. Tracking tool should have the ability of quick, accurate, easy and inexpensive use. Comparative analysis of the planned and actual work efficiency of the machine with the assumption that the planned work efficiency is appropriately calculated, allows detecting the deviation between the theoretical preparation and the field research or detection of lower work efficiency than planned. Spotting the large discrepancies between the planned and actual work efficiency indicates a possible failure in performing earthworks. Then, it is necessary to detect possible critical parameters that jeopardize successful performance of earthworks and explore possibilities to eliminate or reduce their adverse effects and finally, take appropriate corrective actions. Measuring the actual work efficiency of the excavator gives more precise estimation of required time and costs and enables to identify its cost-effective area as a prerequisite for identifying the earthworks sustainability.

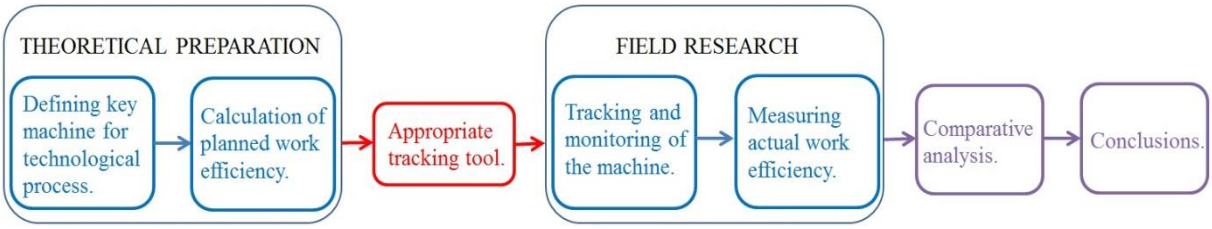

Figure 2. Methodology proposal.

The technological process in this research which was monitored and analyzed was the measurement of the cycle time of the excavator during the loading the tipper trucks on construction site. Theoretical preparation was carried out on the basis of the collected data from the construction site and for conditions that were assumed to run on construction site during the loading of excavated material. Excavator's planned work efficiency was calculated by the formula for calculating the planned work efficiency which includes the reduction coefficient calculated using the existing standardized tables [9–12]. Field research includes measuring i.e. recording the cycle time of the excavator on the construction site. Measurement of the cycle time of the excavator was for the purpose of estimating its actual work efficiency. The used tracking tool was the chronometer with the snapback chronometry method. After each recorded part of loading operation, the counter of the chronometer was reset to zero.

From the viewpoint of optimization and efficiency, the loading was performed by a new excavator, regularly maintained, with optimum power and appropriate tool size. Conditions on construction site were average with good use of working hours. Results of the theoretical preparation and field research were compared and analyzed to determine the deviation between the planned and actual machine work efficiencies. From the comparative analysis and discussion of the results, the corresponding conclusions have been generated.

Manual data collection from the construction site as the snapback chronometry method is outdated, long-lasting, inadequately accurate and requires careful attention in use. However, since this paper analyzes just the work of the excavator during the loading of the tipper trucks, the snapback chronometry method for that purpose represents a practical and simple method for estimating the actual work efficiency of the excavator on construction site.

4. Results and discussion

4.1. On-site conditions during observed technological process

Measurements were taken in July 2017 during the earthworks on the part of a local road, number 233, more precisely, on the construction of Jurčići-Jurjenići-Šporova jama roundabout. Great significance of this road for the city of Kastav is in gaining an alternative traffic route in order to reduce traffic load in the city centre. According to official meteorological station data for the city of Kastav during 20 measurement days, the average day temperature was 21.8°C and the average humidity was 42%. Data was recorded during the loading work of new standard medium size hydraulic excavator (operating weight 23 t) and a net flywheel power of 122 kW into standard transportation vehicle, i.e. tipper truck. Observed excavator was equipped with 1.15 m^3 large bucket, while the maximum bucket size that can be placed on the reach boom is 1.70 m^3.

For the measurement purposes, the observed technological process was divided into four work operations as shown in Figure 3:

- RC1 – clutching the material with excavators' bucket
- RC2 – rotation of excavators boom with the bucket filled with material
- RC3 – loading material into tipper truck
- RC4 – return into start position.

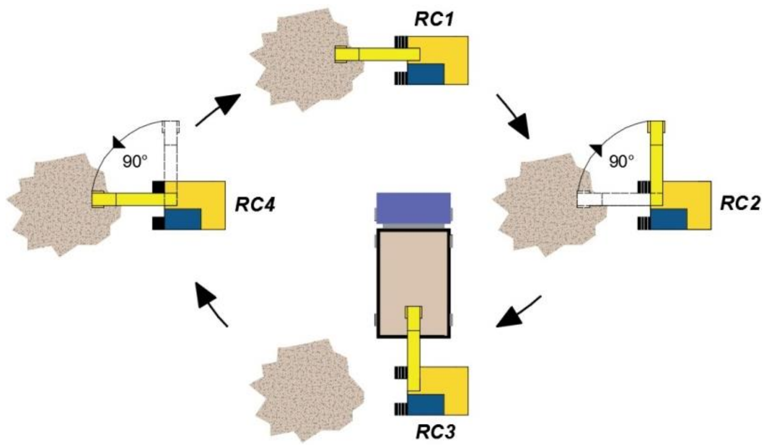

Figure 3. Observed technological process (excavators' loading the tipper truck).

Alongside the machinery and technological process, other data was retrieved from the site (such as material, working condition and organization). Well trained and experienced machine operator had to load the tipper truck with previously excavated mixed material (combination of soil, gravel and rock). The rotation of excavators' boom was 90° (positions RC1 and RC4) and the observed process was done on wide and barrier free area. This information is of great importance in order to describe working environment, especially needed for the calculation of planned work efficiency of standard cyclic construction machine. By using standardized tables [9–12] such information is shaped in a form of reduction coefficient (material coefficient, working condition coefficient and organization coefficient).

4.2. Calculation of standard cyclic construction machine efficiency by standardized tables

The calculation of the construction machinery planned work efficiency is of great importance for determining more realistic duration of machine work on construction site. Such calculation is used for estimation of technological processes duration and therefore the prediction of the whole construction project duration. Construction machinery practical, or planned work efficiency (U_P) is calculated [9–12] by multiplying the machines' maximal efficiency (i.e. theoretical efficiency) with the reduction coefficient (k_R) as is shown in formulas (1) and (2)

$$\boldsymbol{U_P = \frac{q * T}{t_c} * k_R,} \quad (1)$$

$$\mathbf{k_R = k_A * k_B * k_C} \quad (2)$$

Values of the reduction coefficient can be found in standardized tables [9–12] while the selected values for specific conditions during performed measurement on site are shown in Table 1.

Table 1. Selected reduction coefficients.

Name of reduction coefficient	Coefficient value
k_A – material coefficient	$= k_p * k_r * k_{vm}$
k_p – loading bucket capacity	0.85
k_r – material relative density	0.75
k_{vm} – humidity of material	1.00
k_B – working condition coefficient	$= k_{pr} * k_o * k_u$
k_{rp} – working area	1.00
k_o – rotation of the boom	1.00
k_u – for loading operation	0.900
k_C – organization coefficient	$= k_{og} * k_{rv} * k_{ds}$
k_{og} – mechanic work condition	0.80
k_{rv} – utilization working time	0.84
k_{ds} – machine wear and tear	1.00

According to expression (2) and selected values (Table 1), the reduction coefficient (k_R) equals 0.3856.

4.3. Results of the on-site measurement

During on-site measurement the snapback chronometry method was used in order to identify the labour time of each identified work operation (RC1 – RC4). In total, the 200 complete technological processes of the excavators' loading the tipper truck were recorded, i.e. 800 work operations.

Snapback chronometry method is one of time study methods [16] which is frequently used on construction sites to record duration of a single work operation rather than a technological process as a whole [14–15]. Therefore, as each work operation is directly recorded there are some advantages compared to other traditional time study methods [16]:

- Observer error can be calculated
- Irregularities in work can be easily noticed
- Time of justified delays bounded to technological process can be calculated
- Easy recording of delay times during the work which is not connected to technological process
- If the recording is interrupted for any reason it can always be continued.

Table 2 gives an overview of recorded cycles of observed technological process. Beside summary time and rating factor, a normal time of each work operation is shown. While a normal time of each work operation is a product of its average time and related rating factor [16], a normal cycle time (N_{VS}) is a sum of normal times of each operation.

Table 2. Overview of normal cycle time calculation process.

Observed work operation	Summary time					Rating factor	Normal time
	x_{max}	x_{min}	∑x(sec)	∑x(%)	$\bar{x}$		$N_{VS}=\Sigma N_t$
RC1	14.80	2.90	1263.90	28.26	6.320	0.95	N_{tRC1}=6.004
RC2	36.60	2.20	942.80	21.08	4.714	1.01	N_{tRC2}=4.761
RC3	14.40	2.60	887.20	19.84	4.436	0.97	N_{tRC3}=4.303
RC4	54.30	2.10	1378.90	30.83	6.895	1.02	N_{tRC4}=7.033
∑			4472.80		22.365		N_{VS}=22.101

Since the measuring cycles are relatively short when snapback chronometry method is applied in recording cycles of standard cyclic construction machine during the whole machines' working shift, there is a need to additionally multiply the acquired normal cycle time by additional time coefficient (K_D)

$$\mathbf{N_V = N_{VS} * K_D} \tag{3}$$

According to Taboršak [16] and previous site measurements [13–15], such coefficient equals 2.035. Therefore, after additional time correction (equation 3) the normal time of the whole technological process (N_V) equals 44.9755 seconds per cycle or 0.01249 h/cycle.

As the result is acquired per cycle, it is necessary to determine how many cubic meters of loaded material is included in one cycle. For such purpose the observation method [17] is used, as it was estimated that with each bucket clutching and loading only 75% of total bucket capacity is filled. Therefore, by each cycle the total of 0.8625 m^3 is loaded into the tipper truck. According to the aforementioned data, the total measured excavators' actual work efficiency for on-site conditions is 69.05 m^3/h.

4.4. Comparison of results

According to the obtained reduction coefficients, the known excavator shovels (1.15 m^3) and working time at the site (8 h), as well as the varying cycle time, both excavator's work efficiencies were obtained; for measured conditions and from spreadsheets. The comparison of the efficiencies, i.e. their dependence on the cycle time is shown in Figure 4.

From the chart, it is evident that with the increase of cycle duration, the impact of the excavator is reduced, which is logical because it performs less work in the observed time unit (1 h). According to the work efficiencies obtained, unit labour costs are calculated. The total costs include the hour cost of the machine work and the machine worker's hourly rate. The relevant prices are downloaded from the Bulletin, III. 2018 [18]. Figure 5 shows the dependence of excavator unit costs on the cycle time.

By increasing unit cycle times, the unit costs of machine working are linearly growing. In both graphs (Figures 4 and 5) there is a very small difference between work efficiencies obtained by measuring (i.e. actual work efficiencies) and calculating (i.e. planned work efficiencies).

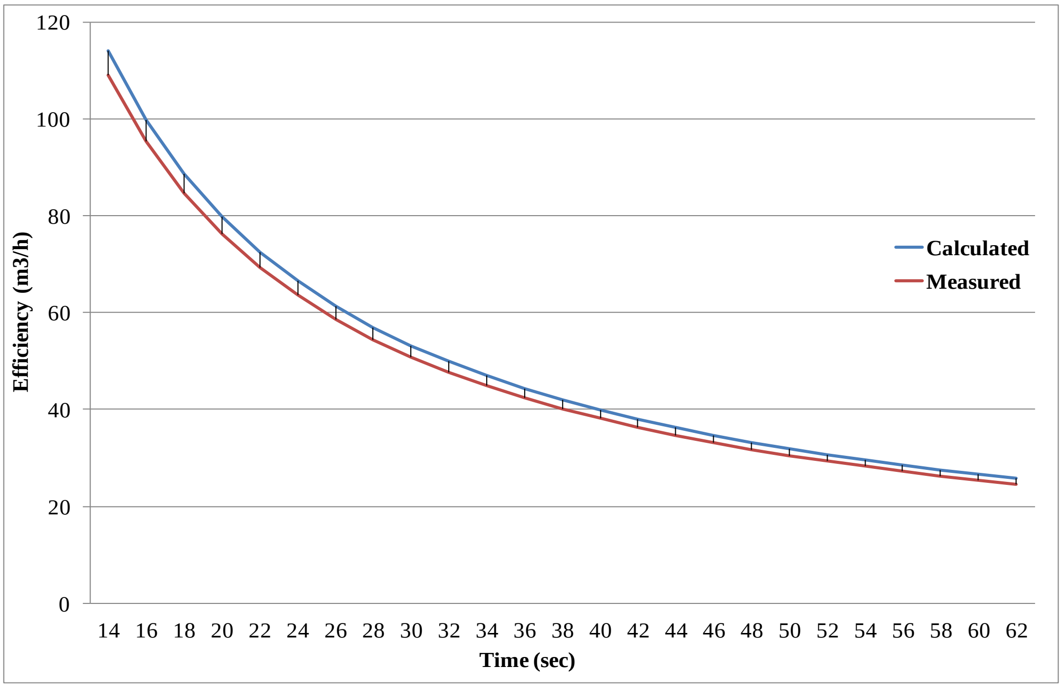

Figure 4. Dependence of excavator work efficiency on unit cycle time.

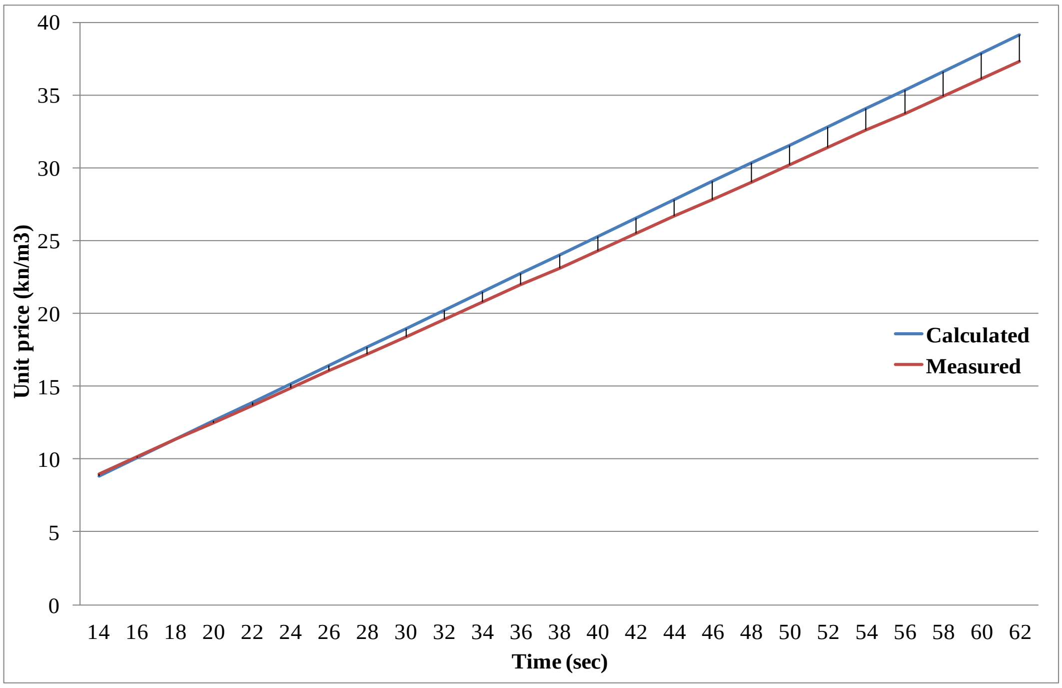

Figure 5. Dependence of the unit costs of the excavator on the unit cycle time.

According to Linarić [9], the basic aim of the machine work planning and the corresponding work performance is that the selected machines or machinery and their corresponding work efficiency give the minimum cost per unit of quality product or minimum cost of the work efficiency. Therefore, the optimum work of the excavator would be at as short as possible cycle duration. Then the highest performance is achieved, and its unit cost is the lowest. In reality, maintaining the shortest possible time cycle is very difficult, almost impossible, because of almost unpredictable circumstances that appear during work. The chart in Figure 6 shows the area where the excavator continues to operate economically with respect to the cycle duration.

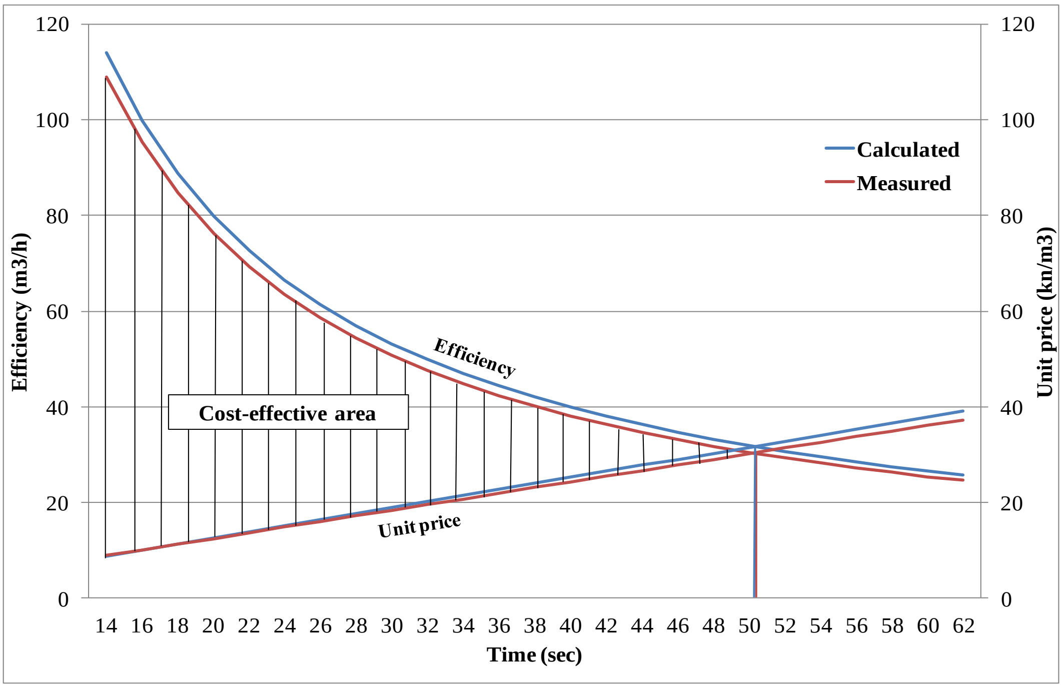

Figure 6. The area of the economical operating of excavator when loading.

The scope of cost-efficiency, for measured performance and costs, as well as those calculated, extends up to about 50 seconds of cycle duration.

5. Conclusions

Measuring the actual work efficiency of the construction machinery represents an aspect of tracking and monitoring the operations as a part of earthworks sustainability. Tracking and monitoring earthworks operations enable correct decision-making, implementation of improvements, more accurate predictions of activity duration, necessary costs and resources as well as early detection of defects in order to take timely implementation of appropriate corrective measures. The aim of this research was to notice the existence of a deviation and examine the differences between planned and actual work efficiency of the excavator during loading the tipper trucks, and to identify its cost-effective area as a prerequisite for identifying the earthworks sustainability. As the earthworks sustainability is the synthesis and concordance of beneficial activities for technological, economic, environmental and social performance context, the balance of excavators' work efficiency is needed. In this research, a comparative analysis of the planned and actual work efficiency has shown that they are approximately equal which gives us confirmation that the work would be carried out according to the plan. It was concluded that in order to achieve sustainability, i.e. to be in cost-effective area, the maximum value of excavators' cycle time extends up to 50 seconds. The next step would be to consider the possibilities and conditions for loading with the shortest possible cycle time in order to improve the efficiency of the excavator.

Proposed methodology allows tracking and monitoring the construction machines with possibilities for increasing their work efficiency, aimed at earthworks sustainability. The key to the successful implementation of this methodology is the selection of the appropriate tracking tool. Since this research analyzes just the work of the excavator during the loading the tipper trucks, the snapback chronometry method for that purpose represents a practical and simple method for estimating the actual work efficiency of the excavator on construction site.

However, for more complex technological processes in the earthworks when selecting the appropriate tracking tool, advanced wireless technologies such as GPS, RFID, and vision-based technologies (photogrammetry and video analysis) should also be considered. Specifically, application of such technologies significantly reduces the possibility of human error. It is certain that the potential of these technologies in not fully explored. Therefore, further research attention to these issues is rightfully expected.

Acknowledgements
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