DETERMINATION OF THE ELEMENTS OF PRODUCTION CYCLE TIME IN SERIAL PRODUCTION: THE SERBIAN CASE

Dragan Ćoćkalo[1], Sanja Stanisavljev[1], Dejan Đorđević[1], Milivoj Klarin[1] and Aleksandar Đ. Brkić[2]
[1]*Technical Faculty "Mihajlo Pupin", University of Novi Sad, Zrenjanin, Republic of Serbia*
[2]*Faculty of Mechanical Engineering, Innovation Center, University of Belgrade, Republic of Serbia*
E-mail: cole@tfzr.uns.ac.rs; dragan.cockalo@tfzr.rs

Received March 2013, Accepted April 2014
No. 13-CSME-113, E.I.C. Accession 3571

ABSTRACT

A model for the stochastic determination of the elements of production cycle time is proposed and experimentally verified in this survey. The originality of the model as reflected in the idea of using a work sampling model to monitor the production cycle is one of the most significant indicators of production effectiveness and efficiency, instead of applying classical methods. It has been experimentally proved that for a corresponding representative set the elements of working time range according to normal distribution law and that, dynamically viewed, it is possible to use mean value calculations to establish control limits on three standard deviations for the individual elements of working time and thus to master the process. Based on our experimental investigations, it has been proved that in the practice of small and medium-sized enterprises with serial production it is possible to design and apply a very simple but accurate enough stochastic model to determine the elements of working cycle time and in this way optimize the duration of production cycle time.

Keywords: production cycle, production cycle time, work sampling, stochastic model.

DÉTERMINATION DES COMPOSANTES DU TEMPS DE CYCLE DANS LA PRODUCTION EN SÉRIE: LE CAS DE LA SERBIE

RÉSUMÉ

Un modèle de détermination stochastique des éléments du Temps de Cycle sera proposé et vérifié expérimentalement dans cette étude. L'originalité du modèle est reflétée par l'usage d'un modèle d'échantillonnage du travail pour contrôler le cycle de production, grâce à l'efficacité et au rendement, indicateurs de production les plus significatifs, plutôt que d'appliquer les méthodes classiques. Cela a été prouvé expérimentalement que, pour un ensemble de variables données, les composantes du temps de travail s'accordent sur la loi de distribution normale et que, d'un point de vue dynamique, il est possible d'utiliser un calcul de moyenne pour établir des limites de contrôle sur trois déviations standards des composantes du temps de travail et ainsi contrôler le processus. Selon les résultats de nos expériences, il est possible, pour des entreprises petites et moyennes avec une production en série, de créer et mettre en place un modèle stochastique suffisamment simple et précis pour déterminer les éléments du temps de travail et ainsi optimiser le temps de cycle.

Mots-clés : cycle de production; durée d'un cycle de production; échantillonnage de travail; modèle stochastique.

NOMENCLATURE

AC, BC, CC	control limits
n	number of items for production in a series
SD	standard deviation
t_{pc}	production cycle time
t_p	production time
t_t	technological time
t_{pt}	set-up time
t_m	manufacturing time
t_c	control time
t_{tr}	transport time
t_{pk}	packing time
t_{mr}	stoppage due to materials
t_{tl}	stoppage due to tools
t_o	stoppage due to organization
t_b	stoppage due to breakdown
t_{to}	stoppage due to other factors
t_{oi}	time of individual operations duration

1. INTRODUCTION

The most important organizational-technical indicators of production successfulness are the level of capacity utilization and the production cycle. These indicators are actually influenced by a series of organizational-technical, mutually interconnected, factors which impact on the elements of working time related to the machine capacity utilization and production cycle of a certain product. The goal is, in general, to reduce the total production cycle time, especially that associated with different types of stoppage and the optimization of both lead and machine time within the sphere of machine capacity utilization. Increased attention was focused on the level of machine capacity utilization because machines are more costly and thereby have a greater impact on production effectiveness. Additionally, the optimization of time for transport, control, and packing is also important for the production cycle. Reduced cycle time can be translated into increased customer satisfaction. Quick response companies are able to launch new products earlier, penetrate new markets faster, meet changing demand, and make rapid and timely deliveries [1]. They can also offer their customers lower costs because quick response companies have streamlined processes with low inventory and less obsolete stock.

On an experimental example, Niebel [2] illustrates the determination of the elements of production cycle (PC) time, showing that production cycle C is divided into only three elements of cycle time, $C = T_1 + T_2 + T_3$ (T_1 = running time to produce one unit of output, T_2 = normal time to service a stopped machine, T_3 = time lost by normal operator working because of machine interference). To ensure rational production and adherence to time schedules in production, quality planning of production and corresponding technical-technological calculations are needed to provide machine operating modes and time duration of machine operations as well as activities involved in the manufacturing process. In this way, they are normed, normalized and standardized, so the elements of PC time can be determined in advance for machines, mechanization means and manual work. In practice, they are not deterministic but stochastic, especially in small and medium-sized businesses and as such need to be monitored.

2. PROBLEM STATEMENT

The application of the modified work sampling method in the processing industry indicates that the methods of monitoring capacity utilization applied in the processing industry such as cement production may

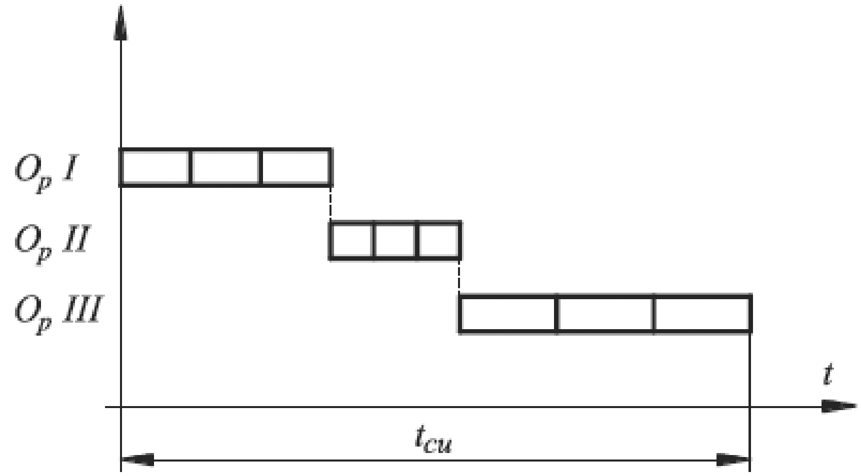

Fig. 1. Organization of a consecutive type of operations sequence.

also be used in the metalworking industry which has a high level of capacity utilization. Hence, the results of the analysis indicate that when the level of capacity utilization is high, this variable may be observed per day as stochastic, while, per machine, it may be a random variable [3]. It is evident that today the more significant problem of monitoring and influencing the production cycle (the period from the item's entry into the production process to the receipt of a finished product and its packing) is far less present in the literature. Although the technical-technological indicator of machine utilization level, i.e., the operation time against total available machine time, is a very significant indicator in production and business operations and the stochastic model application itself is very simple, it is more important to obtain those levels for the elements of PC time. PC time involves the time needed to make a unit or series of units from putting them into production until their storage, and aside from being significant as a technical indicator, it is also important as an economic indicator of freezing current assets, especially raw materials. The vast majority of enterprises monitor PC time through documentation and analysis, but they rarely monitor the elements of work within the PC and by analyzing those elements affect their reduction and thereby PC time reduction.

This is the reason why in this paper we prove experimentally the applicability of the original stochastic method to determine the elements of PC time using the results obtained from screening two plants with small-scale production as an example. In theory, PC time (t_{pc}) is divided into production time (t_p) and non-production time (t_{np}). It is then further divided into technological time (t_t), manufacturing time (t_{tm}) and preparation-finish time (t_{pf}), and non-technological time (t_{nt}) with control (t_c), transportation (t_{tr}) and packaging (t_{pk}) time [2, 4]. Non-production time is classified according to various causes of stoppages in production, and we have carried out a screening of the most general and common ones caused by the lack of raw materials (t_{mr}), breakdown and deficit tools (t_{tl}), organization (t_o), machine breakdown (t_b) and other problems (t_{ot}) [5]. The representativeness of the screening sample per number and time of screening was established by mathematical parameters, SD and control limits, where the elements of PC time are observed as the elements of the process function. The organization of a sequence of operations, and in this regard the determination of machine time (ttm) has the greatest impact on production time as the most important PC time in small-scale and serial production. The organization of a sequence of operations can be consecutive, parallel or combined. In a consecutive operations sequence, production proceeds in such a way that the entire series of units waits for all the units of a series to be completed on one machine, and only afterwards is removed all together onto another machine (operation), as is evident from Fig. 1.

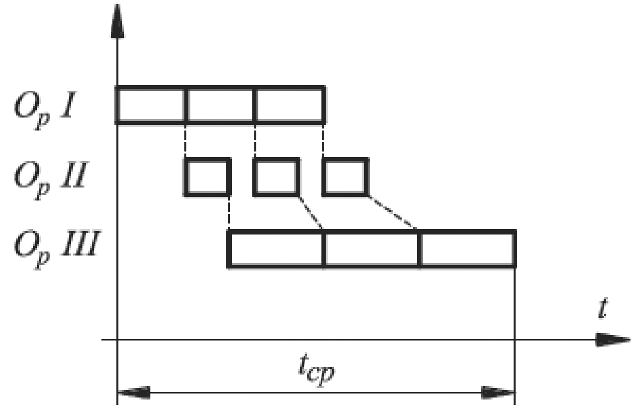

Fig. 2. Organization of parallel type of operations sequence.

In a consecutive type of operations sequence, the total time necessary for a series production, i.e. production cycle length is

$$t_{cu} = n \cdot \sum_{i-1}^{k} t_{oi}, \tag{1}$$

where n is the number of items for production in a series, k is the number of operations for producing an item, t_{oi} is the time of individual operations duration.

Figure 2 shows the organization of a parallel type of operations sequence. The time required for making the series is obtained on the basis of

$$t_{cp} = (n-1)t_{o\max} + \sum_{i=1}^{k} t_{oi}. \tag{2}$$

It is obvious from Figs. 1 and 2 that for the identical time duration of technological machine time observed for the machine operating mode for three operations of three-unit-series, the PC time is much longer in the consecutive type of operations sequence. In effect, the PCs in Figs. 1 and 2 represent only manufacturing time that involves the waiting time for the operation beforehand and the worker's manual work time related to a single unit. Therefore, manufacturing time should be distinguished when the machine capacity is analyzed [6] and when the PC time is analyzed and monitored. This refers particularly to serial production, when the work sampling method is applied and, in general, work study is performed. Consequently, the aim of this paper is to set up a model for the stochastic determination of the elements of production cycle time. Using a modified work sampling method, it has been experimentally proved in this paper that for a corresponding representative set the elements of working time range according to normal distribution law. Also, dynamically viewed, it is possible to use mean value calculations to establish control limits on 3 standard (±3SD) deviations for some individual elements of working time and thus to master the process.

The parallel production type is mainly used in high series production and its imperfection lies in the emergence of stoppage in machine work related to short operations, so for small series production a combined type is more favorable because it solves this problem in the following way – for shorter operations, production is planned backwards from the last part in the series. A higher level of work organization is necessary in this case, but unfortunately, our observed organizations have not yet reached this level. Preference for production type is obtained by the data on the used machines (capacity) and it is possible to obtain this information by the work sampling method. Therefore, by recording the production cycle the problem of the engaged means would be solved and by recording the possibilities of use the results would be even better if a combined type were to be applied. A combined production type is shown in Fig. 3.

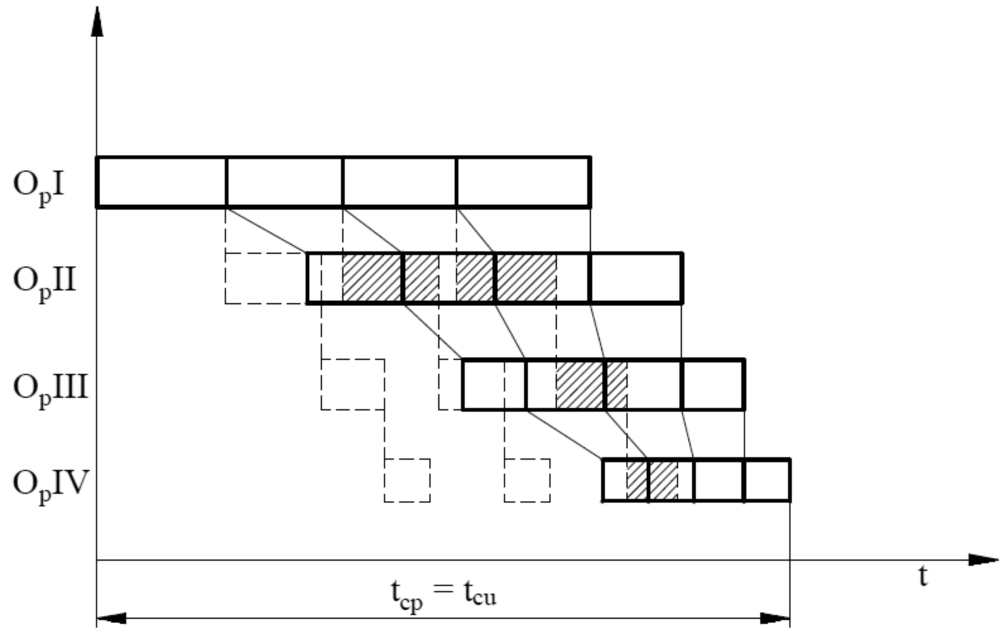

Fig. 3. Combined production type.

Materials Requirements Planning (MRP), originally introduced by Orlicky [7] as "an effective way explicitly to consider the relationships between the end items and the various components and sub-assemblies" is still the philosophy employed by the majority of manufacturing enterprises for production planning. Agrawal et al. [8] improved the MRP approach to MRP-based production planning by means of targeting minimal product cycle times. A number of works [9, 10] considered the impact of machine breakdown on production cycle time, while Barbiroli and Raggi [11] studied technical and economic performance related to innovations in the production cycle environment. Kun-Jen Chung et al. [12] linked an inventory model with production cycle optimization, whereas Kodek and Krisper [13] give an optimal algorithm for minimizing production cycle time for assembly lines, using linear mathematical programming which requires extensive calculations.

The elements of PC time may be monitored by using the work sampling method, which was originally applied in the textile industry by Tippett [14–16], and researched in the surveys of Barnes [17], Moder [18] and Richardson and Eleanor [19]. However, the original method has a restricted realm of use, and only three elements of PC time were monitored: the machine is in operation, the machine is in preparation, or the machine is idle ($+$, $\times$, $-$). Nevertheless, the classic work sampling method established by Tippett and others is not appropriate for contemporary production systems, because in his research the main stoppage was due to poor material quality. The indispensible modification of the method presented by Klarin et al. [6] aims to explain and justify both the necessity and importance of using the shift level of capacity utilization as the stochastic variable in determining the total level of capacity utilization in the production process by using the method of work sampling on a sample comprising 74 Serbian companies. The conclusion drawn is that the shift level of capacity utilization as the stochastic variable in work sampling is the model which solves the problem of determining the total level of capacity utilization in a convenient way with accurate results. On the other hand, on the basis of the mentioned research, Elnekave and Gilad [20] propose a digital video-based approach to enhance work measurement and analysis by facilitating the generation of rapid time standards, which serves as a computerized tool for remote work measurement with the ability to derive the rapid generation of time standards. Radojković et al. [21, 22] used the modified method of current observations, a new method that has the same technology and mode as its classical counterpart, but with the modification whereby we observe only those work positions where the worker and the object of production are the key objects.

3. METHODOLOGICAL OVERVIEW

3.1. The Basics of a Stochastic Model to Determine the Elements of Production Cycle Time

The production cycle is the period from the entry of a product part or series of products into manufacturing to their receipt in the warehouse of finished products (or parts). The production cycle is indirectly dependent on the factors of the total supply-sales cycle as its part, but some elements of cycle time are also mutually influential. For example, any increase in the supply time for parts from cooperating companies leads to a stoppage in the production cycle. For the purpose of analysis, the production cycle is essentially divided into production time (t_p) and non-production time (t_{np}) [5]. Non-production time involves diverse stoppage factors related directly or indirectly to man's positive or negative attitude towards production. These stoppages, characteristic of small and medium-sized enterprises in the metalworking industry, are, as a rule, longer than the necessary production times and are more difficult to shorten. The optimal production cycle is that which is the shortest for the same product quality and price. The most common division of production cycle time is presented in Fig. 4.

Our investigation is directed at designing a new original method for monitoring the production cycle and its time elements by using a stochastic work sampling method, whose basis was established by Tippett. However, this method will be innovated and adapted to an investigation of the production cycle. A modified work sampling method will enable the determination of the participation percentages of working time elements against the total duration of the production cycle and production. The fact that this method is statistic and based on a certain number of instantaneous observations of a given activity makes it simpler to use and more efficient than the continual streaming method. Monitoring within the production cycle will involve technological time with preparation-finish time (this includes the reception of orders for work with documents and the study of tasks, the reception of tools, and the preparation of other work elements), manufacturing time (the time spent on the manufacturing of a product, machine work), non-technological time with times for transport (the time spent on the transportation of materials and semi-products from one production place to another), control (the time spent on the control of product quality during production and the control of finished products) and packing (the time spent on the packing of finished products), while non-production time includes stoppage due to poor production organization, lack of materials, lack of tools, including the failure or breakdown of machinery and other types of stoppage, their interdependence, as well as impact factors such as series size, organizational level and product characteristics pertaining to the factors mentioned. Non-production time includes stoppages in production which cause failures in the production cycle. As the names and signs of non- production time denote, stoppages are usually caused by: discrepancies in production processes, "bottlenecks" in production, lack of appropriate input (material, tools, energy), bad organization and servicing jobs, poor quality, accidental stoppage caused by undisciplined workers, damage and breakage of tools and machinery, and lack of tools.

Representative screening time is related to the length of the production cycle time. It is clear that it must not be shorter than the production cycle time and that under identical production conditions it must be repeated a certain number of times in order to make the sample representative. Production and productivity are also related to the production dynamics which are planned at the operational level on a daily, weekly or monthly basis. Hence, the production cycle for the above mentioned periods is also provided for the purposes of monitoring and comparison. The third criterion for determining screening time duration is the adopted margin of error in the stochastic model applied in these investigations, i.e. the number of instantaneous observations and their distribution per working time element.

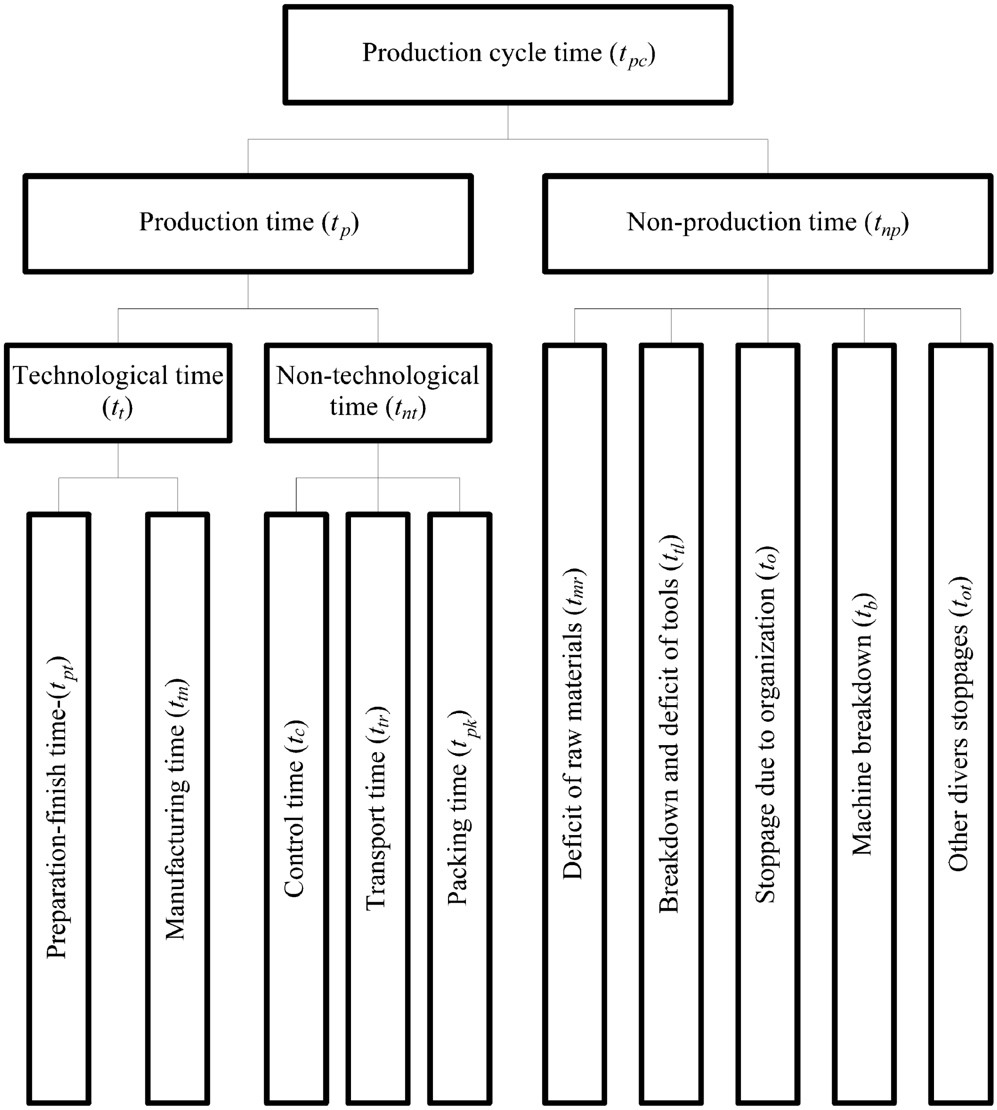

Fig. 4. Production cycle elements.

3.2. The Problem of Determining Technological Time

Screening performance requires the precise definition not only of technological and mathematical problems, but also of the practical screening process and the establishment of working time elements. Thereafter, the elements of production cycle working time should be defined and, in particular, the difference when compared with the elements of working time related to machinery, i.e. for the purpose of establishing the machine capacity only or within the production cycle, because these two are not the same. The elements of working time are determined according to Barnes [17], Maynard [4], Moder [18], Niebel [2], Richardson and Eleanor [19], Klarin et al. [1, 3], and Čala et al. [5]. Theoretically speaking, the sequence of operations may be serial, parallel or combined.

Therefore, depending on the type of operations sequence, we know in advance that this portion of cycle time lasts much longer in a serial type, where before moving on to the next operation the whole series waits to be completed by a single machine operation, while in a parallel type, after one machine part is completed on one machine, it immediately moves on to the next. In companies, the most common type of operations sequence is combined. Not infrequently, one part of the production cycle is parallel, another serial, and a third combined. Manufacturing time (ttm), viewing production against machinery, is exclusively linked to machine performance and the quality of technological calculations, and is mainly a deterministic category.

However, if the production cycle is viewed from the aspect of a serial operations sequence, the elements of working time differ, depending on the automation level. If production is automated, then (ttm) for a series will be simply the sum of individual n equal operations. However, if each part has to be manually or mechanically conveyed for processing from a joint crate or some other room where a certain series of parts is stored, manual placement on the machine will be the ancillary manual time (t_{pr}). In theory, this refers to individual pieces. Such time is not frequently encountered in the literature (rare examples are papers by Klarin et al. [2, 5]) dealing with the division of working time elements. In our investigations, ancillary manual time will be treated as manufacturing time (t_{tm}). It is also logical to add ancillary machine time (for example, support moving a lathe) to (t_{tm}). Manufacturing lead time includes the reception of work orders with documentation and the study of tasks, the reception of equipment, the preparation of other components necessary for work, the transportation of finished pieces for quality control and the cleaning up of the work place after a certain number of pieces (n) are manufactured, one at a time, non-stop (the number of pieces in a series).

4. APPLICATION OF THE MODEL FOR THE STOCHASTIC DETERMINATION OF PRODUCTION CYCLE TIME ELEMENTS

The practical application of establishing the mentioned elements of PC time is reduced to instantaneous observations of time elements, where the object of labor moves through the production operations list. A series of units is distinctly marked by this document and an analyst (recorder) can readily identify it. Screening is conducted according to randomly chosen times that are entered on a screening sheet. The screening sheet is related to one PC, and the number of individual elements of work; i.e. the frequencies, are recorded on it. The data in Table 1 are thus formed. Using the frequencies, we first calculate the % of the individual elements against the total PC time, and then based on the analytical screening of the PC time duration, the time duration of the individual elements of working time is calculated.

The organization of the operations sequence in both enterprises where screenings were performed was of the consecutive type. The research of the model was conducted in the second half of 2011 and involved a larger number of Serbian enterprises. The results obtained for two characteristic enterprises will be presented here. The first most extensive experiment is related to an enterprise owned by a large German firm engaged in manufacturing car components. The screenings were performed from September 19, 2011 to November 4, 2011. The monitoring included 47 cycles of different series sizes (4–10 units) and the time duration ranged from the shortest (240 min) to the longest (420 min), with 10–30 instantaneous observations. The screening results are shown in Tables 1(a–c), where only the first 5 cycles of 47 are given as well as the total result for all 47 cycles. The results are displayed per number of instantaneous observations of working time elements, the percentage of their participation in the total duration and per element of working time, as well as the total average values and standard deviations – SD.

The analysis of two cases, metal manufacturing and textile enterprises, are given. Although they are different and deal with different products, they can be observed in the same way through the application of the stochastic model to determine the elements of working cycle time.

There were 932 observations in total, and the total time for all cycles amounts to 15,293 min. The average production cycle time (t_{pc}) is 325 min and the average production cycle time per unit (t_{pcu}) is 56.2 min. Investigations related to the coefficient of running time as a function of the series size and where the PC

Table 1a. Production cycle elements according to frequency of occurrence.

Date	Number of observations	Time		Production time					Non-production time					Number of pieces
		Start	End	t_{pt}	t_{tm}	t_c	t_{tr}	t_{pk}	t_{mr}	t_{tl}	t_o	t_b	t_{ot}	
19.09.'11.*	26	8:30	13:00	3	9	3	1	2	2	–	2	1	2	7
26.09.'11.	18	8:05	13:30	2	5	2	4	3	1	–	–	–	1	10
23.09.'11.	21	–	–	–	–	–	–	–	21	–	–	–	–	canceled
19.09.'11.*	31	8:30	13:00	2	9	3	3	3	2	1	2	1	4	7
19.09.'11.*	22	8:20	13:10	2	7	4	1	3	1		2	2	8	
...														
N														
$\sum$	**932**			**100**	**229**	**118**	**142**	**99**	**47**	**3**	**25**	**15**	**154**	

*19.09.'11. Three observers worked parallel because there are more series simultaneously, the administrative time is the same.

Table 1b. Production cycle elements percentages of elements.

Date		Time		Production time					Non-production time					Number of pieces	t_{pcu} (min/pc)
	t_{pc}	Start	End	t_{pt}	t_{tm}	t_c	t_{tr}	t_{pk}	t_{mr}	t_{tl}	t_o	t_b	t_{ot}		
19.09.'11.*	270	8:30	13:00	12	36	12	4	8	8	–	8	4	8	7	38.6
26.09.'11.	325	8:05	13:30	11.11	27.78	11.11	22.22	16.67	5.56	–	–	–	–	10	32.5
23.09.'11.	310	–	–	–	–	10	–	–	100	–	–	–	–	canceled	0
19.09.'11.*	270	8:30	13:00	6.7	30	18.18	10	10	6.7	3.3	6.7	3.3	13.3	7	38.6
19.09.'11.*	290	8:20	13:10	9.09	31.82	31.82	4.55	13.64	4.55	–	–	–	–	8	36.3
...															
H	**100**			**0.107**	**0.246**	**0.127**	**0.152**	**0.106**	**0.05**	**0.003**	**0.27**	**0.016**	**0.165**		

Table 1c. Production cycle elements according to time duration.

Date		Time		Production time					Non-production time					Number of pieces	t_{pcu} (min/pc)
	t_{pc}	Start	End	t_{pt}	t_{tm}	t_c	t_{tr}	t_{pk}	t_{mr}	t_{tl}	t_o	t_b	t_{ot}		
19.09.'11.*	270	8:30	13:00	32	97	32	11	22	22	–	22	11	22	7	38.6
26.09.'11.	325	8:05	13:30	36	90	36	72	54	18	–	–	–	18	10	32.5
23.09.'11.	310	–	–	–	–	18	–	–	310	–	–	–	–	canceled	0
19.09.'11.*	270	8:30	13:00	18	81	26	27	27	18	9	18	9	36	7	38.6
19.09.'11.*	290	8:20	13:10	26	92	53	13	40	13	–	26	–	26	8	36.3
...															
$\sum$	**15293**			**1632**	**3762**	**1939**	**2413**	**1709**	**704**	**40**	**376**	**271**	**2465**		

was analytically monitored from the plants records did not include an in-depth analysis of the relationships between the series. Our investigations will present the analysis of the PC time observed per group as determined by the series size. Table 2 shows the data for the groups and the PC mean values per unit in a series (t_{pcu}) (min/unit) as well as the PC time (t_p) for the same groups in % and $SD_p(\%)$. Table 3 displays the same data without the groups but with the number of screening cycles and the number of units in those cycle series, with the total mean value of the PC time ($\bar{\bar{t}}_p$) in % which amounts to 76(%).

The trends of PC time mean values ($\bar{t}_{pi}$) by cycles (groups) with an identical number of units in a series in % and the PC mean values per unit in a series ($\bar{t}_{pcu}$) are given in Fig. 5. The mean value for all groups is obtained using

$$\bar{\bar{t}} = \sum \frac{\bar{t}_{pi} \cdot f_i}{N}, \tag{3}$$

where f_i is the number of cycles in a group and N is the total number of cycles, or

$$\bar{\bar{t}}_p = \frac{85.41 \cdot 3}{46} + \cdots + \frac{79.75 \cdot 3}{46} = 76(\%).$$

Table 2. Production cycle time per unit in a series and production time in %.

Number of items (n)	t_{pcu} (min/kom)	t_p (%)	SD_{tp}(%)
3	80	75	7.42
3	96	91.77	
3	103.3	89.47	
$\bar{x}$	$\bar{t}_{pcu} = 93.1$ (unit/ser)	$\bar{t}_{pt} = 85.41$(%)	
4	80	85	16.14
4	73.25	70	
4	71.25	76.47	
4	65.4	93.75	
$\bar{x}$	$\bar{t} = 72.48$ (unit/ser)	$\bar{t} = 81.31$(%)	
5	60	78.95	28.04
5	69.6	70	
5	61.6	85.71	
5	70	75	
5	65.4	78.95	
5	67.2	95.24	
5	49.2	61.54	
5	67.2	80.95	
5	63.8	70	
5	55.4	66.67	
5	63.4	76.47	
5	65.4	78.95	
5	69	77.27	
5	70	70	
5	64	70	
5	54	81.82	
5	66	61.91	
5	71	70	
$\bar{x}$	$\bar{t}_{pcu} = 63.29$ (unit/ser)	$\bar{t} = 74.97$(%)	
6	51.5	73.91	29.64
6	52.5	64.71	
6	58.5	58.09	
6	58.5	63.63	
6	58.5	59	
6	61.2	85.72	
6	61.2	86.43	
6	53.3	80.96	
6	53.3	74.08	
6	61.7	61.91	
$\bar{x}$	$\bar{t}_{pcu} = 57.02$ (unit/ser)	$\bar{t}_{pi} = 70.84$(%)	
7	38.6	72	16.91
7	38.6	66.7	
7	53.3	91.3	
$\bar{x}$	$\bar{t}_{pcu} = 43.50.1$ (unit/ser)	$\bar{t}_{pi} = 76.67$(%)	
8	36.3	73.27	10.07
8	51	85.7	
8	51	75	
8	47.3	73.69	
8	41.9	81.25	
$\bar{x}$	$\bar{t}_{pcu} = 45.50$ (unit/ser)	$\bar{t}_{pi} = 77.78$(%)	
10	32.5	88.88	10.53
10	32.5	76.47	
10	42	73.91	
$\bar{x}$	$\bar{t}_{pcu} = 35.67$ (unit/ser)	$\bar{t}_{pi} = 79.75$(%)	

Table 3. Number of cycles and number of units in a series for enterprise I.

No.	No. of cycle (f_i)	unit/ser	$\bar{t}_{pcu}$ (unit/ser)	$\bar{t}_{pi}$ (%)	SD_{tp}
1	3	3	93.10	85.41	7.42
2	4	4	72.48	81.31	16.14
3	18	5	63.29	74.97	28.04
4	10	6	57.02	70.84	29.64
5	3	7	43.50	76.67	16.91
6	5	8	45.50	77.78	10.07
7	3	10	35.67	79.75	10.53
	$N = 46$			$\bar{\bar{t}}_p = 76(\%)$	

SD_p denotes the standard deviation of all the elements of the production time to the time for a non-stratified set of data from Tables 2 and 3, using the following:

$$\mathrm{SD}_p = \sqrt{\frac{\sum_{j=1}^{k} \left(\bar{t}_{pi} - \bar{\bar{t}}_p\right)^2 \cdot f_i}{N}} = 9.606(\%). \tag{4}$$

The control limits are

$$\begin{aligned} CC &= \bar{\bar{t}} \pm 3 \cdot \bar{\bar{t}}_p \cdot \mathrm{SD}_p \\ CC &= 76 \pm 3 \cdot 76 \cdot 0.09696 = 76 \pm 21.9(\%) \\ AC &= 97.9(\%) \\ BC &= 54.1(\%). \end{aligned} \tag{5}$$

It is obvious from Fig. 5 that, mathematically viewed, the process is mastered, because all the points of $(\bar{t}_{pi})$ lie within the control limits $BC < \bar{t}_{pi} < AC(54.1 < 76 < 97.9)$. The trend of (t_{pcui}) can be approximated by the function

$$\bar{t}_{pcu} = \frac{b}{n} + c = \frac{297.54}{n} + 1.998, \tag{6}$$

where n is the number of units.

The statistical set stratification was not been successful because the SD of the stratified set is

$$\begin{aligned} \sigma' &= \sqrt{\bar{\sigma}^2 + \delta^2}, \\ \sigma' &= 27.19(\%) \end{aligned} \tag{7}$$

$$\mathrm{SD} = \sqrt{(t_{oi} - \bar{t}_p)^2}, \tag{8}$$

$$\bar{\sigma}^2 = \frac{\sum_{j=1}^{k} \sigma_j^2 \cdot n_j}{n}, \tag{9}$$

$$\delta^2 = \frac{\sum_{j=1}^{k} (\bar{t}_p - \bar{\bar{t}}_p)^2 \cdot n_j}{n}. \tag{10}$$

The $\mathrm{SD}_p < \sigma'$ $(9.606 < 21.19)$ means that the stratification was unsuccessful, which in turn demonstrates that in this enterprise there is no feature distinguishing the PC with a different number of units in a series, but the reduction of time per unit is exclusively the result of technological time, i.e. the elements of working time and the number of units. The screening procedure in enterprise II was performed in an identical way to that

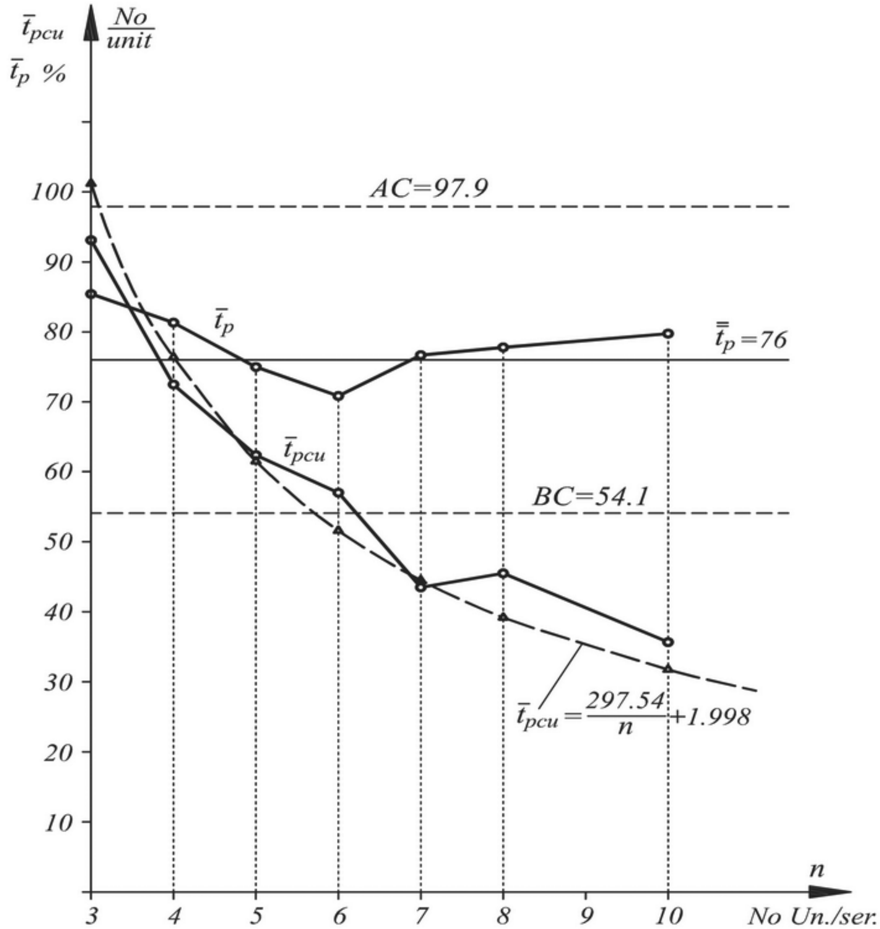

Fig. 5. Trends of production time ($\bar{t}_p$) mean values and PC mean values per unit in a series ($\bar{t}_{pcu}$) for enterprise I.

in enterprise I. The second experiment is related to a plant that produces military and fireman clothing. The screenings were carried out from September 27, 2011 to November 13, 2011. The monitoring comprised 26 production cycles of different types of clothing and different series sizes ranging from 9–117 units, with time durations from 355 min for the shortest to 3700 min. for the longest, while instantaneous observations ranged from 21–90. The data were processed in the same way as for enterprise I according to the data structure presented in Table 1, with the data obtained for enterprise II shown in Tables 4 and 5. The data given in the tables represent the mean values and SDp for groups of screenings for PCs per series size. It is noticeable that there are 11 groups containing at least 9 units in a series, while the largest group has 115 units in a series.

Table 4 shows the size of each group with the number of units in a series for the PC time per unit (t_{pcu}), the production time (t_p) and the mean values per group and SDp in % for (t_p). Table 5 displays the mean values ($\bar{t}_p$) and ($\bar{t}_{pcu}$), SD$_p$ and the number of PCs screened according to groups and the number of units in a series in those cycles. Table 5 also shows the log taken for the number of units in a series – log (unit/ser), so the trends for the presented working time elements are given in Fig. 6.

The mean value obtained for all the groups using Eq. (3) is $\bar{\bar{t}}_p = 70.53(\%)$ and that obtained using Eq. (5) ranges from the bottom control limit $BC = 63.92(\%)$ to the upper control limit $AC = 77.14(\%)$. The stratification of groups was again unsuccessful, because according to Eq. (4) SD$_p = 4.5(\%)$ and based on Eq. (7) $\sigma' = 4.584(\%)$, which is approximately equal. The trend of (t_{pcui}) can also be approximated by a

Table 4. PC time per unit in a series and production time in % for enterprise II.

Number of items (n)	t_{pcu} (min/kom)	t_p (%)	SD_{tp}(%)
9	53.33	67.2	0.99
9	53.33	67.22	
$\bar{x}$	53.33	66.21	
10	52	59.26	5.64
10	46	62.49	
10	87.6	72.56	
$\bar{x}$	61.87	64.77	
12	66.08	67.44	2.07
12	65	70.21	
12	63.33	72.5	
$\bar{x}$	64.8	70.05	
14	37.14	76.19	3.32
14	38.57	69.56	
$\bar{x}$	37.86	72.88	
17	54	75.68	5.22
17	54	74.36	
17	54	63.16	
17	37.65	73.6	
17	37.65	80.64	
17	35.88	74.08	
$\bar{x}$	45.53	73.59	
18	34.44	66.67	0
$\bar{x}$	34.44	66.67	
63	15.87	75	0
$\bar{x}$	15.87	75	
67	15.82	70.4	0
$\bar{x}$	15.82	70.4	
106	13.4	71.95	1.22
106	13.4	69.69	
106	13.21	69.13	
$\bar{x}$	13.27	70.26	
112	8.64	72.33	0
$\bar{x}$	8.64	72.33	
115	7.19	71.8	0.41
115	6.96	71.87	
115	6.96	70.97	
$\bar{x}$	7.04	71.55	

similar function as for enterprise I and by using Eq. (6), however, the log was taken for the number of units because of the drawing scale, or

$$\bar{t}_{pcu} = \frac{b}{\log n} + c \tag{11}$$

The diagram in Fig. 6 shows the trend of production time ($\bar{t}_p$) mean values and PC mean values per unit in a series ($\bar{t}_{pcu}$) for enterprise II.

The mean value obtained for all the groups using Eq. (3) is $\bar{t}_p = 70.53(\%)$ and ranges from the bottom control limit $BC = 63.92(\%)$ to the upper control limit $AC = 77.14(\%)$. The stratification of groups was again unsuccessful, because according to Eq. (4) $\mathrm{SD}_p = 4.5(\%)$ and based on Eq. (7) $\sigma' = 4.584(\%)$, which is approximately equal. The trend of (t_{pcui}) can also be approximated by a similar function as for enterprise I and by using Eq. (6), however, the log was taken for the number of units because of the drawing scale. The trend of ($\bar{t}_{pcu}$) again can be approximated by the function shown in Eq. (11), where $c = -5.25$ and $b = 690$.

Table 5. Number of cycles and number of units in a series for enterprise II.

No.	No. of cycle (f_i)	unit/ser	$\bar{t}_{pcu}$ (unit/ser)	$\bar{t}_{pi}$ (%)	SD$_{tp}$	log (unit/ser)
1	2	9	53.33	66.21	0.99	0.954
2	3	10	61.87	64.77	5.64	1
3	3	12	64.80	70.05	2.07	1.079
4	2	14	37.86	72.88	3.32	1.146
5	6	17	45.53	73.59	5.22	1.23
6	1	18	34.44	66.67	0.00	1.255
7	1	63	15.87	75.00	0.00	1.799
8	1	67	15.82	70.40	0.00	1.826
9	3	106	13.27	70.26	1.22	2.021
10	1	112	8.64	72.33	0.00	2.049
11	3	115	7.04	71.55	0.41	2.061
	$N = 26$			$\bar{\bar{t}}_p = 70.53(\%)$		

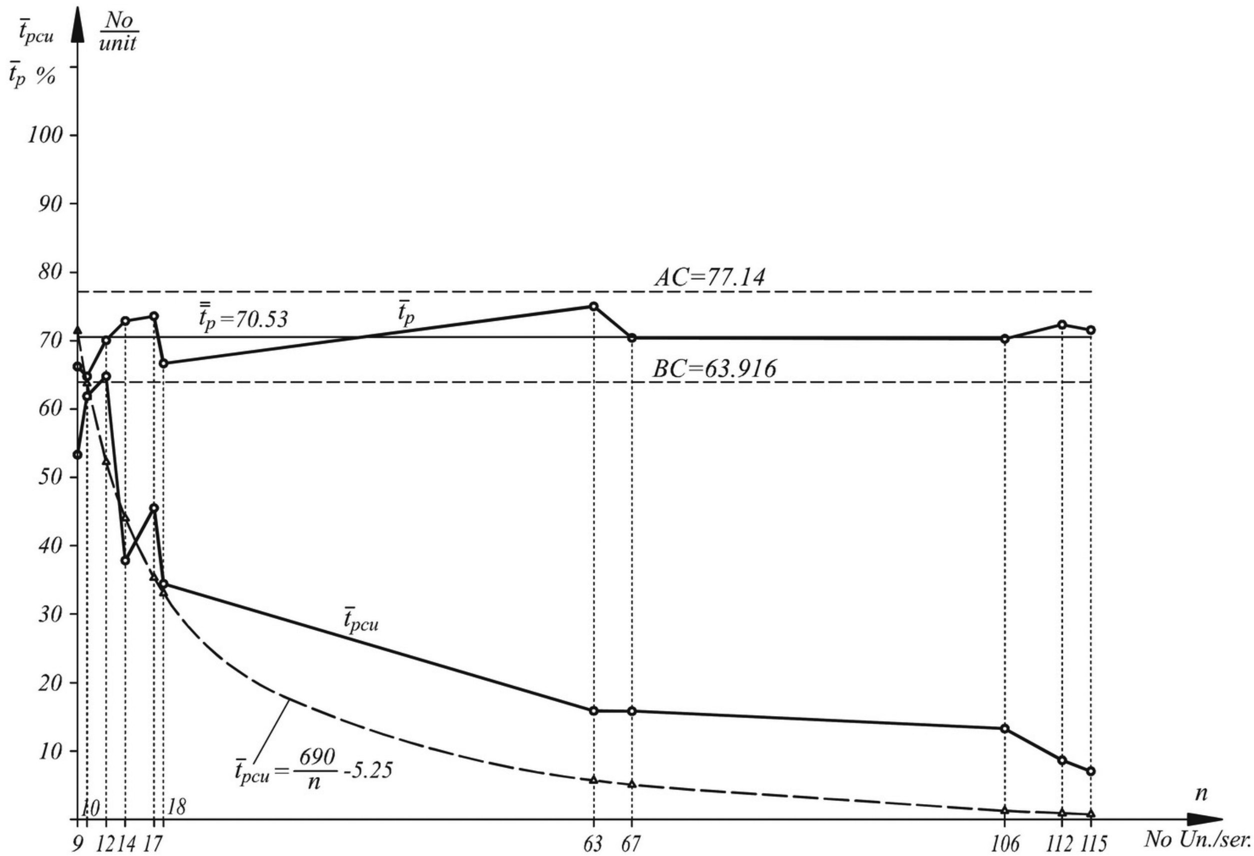

Fig. 6. Trend of production time ($\bar{t}_p$) mean values and PC mean values per unit in a series ($\bar{t}_{pcu}$) for enterprise II.

It can be noticed that the movements of PC time elements are similar to those from the first enterprise. Although the number of monitored production cycles is considerably smaller in this enterprise (26), the stochastic variable of production time is more stable. The minimum deviations of the control limits have only two points (two PC samples) which exceed the upper limit.

If we compare the enterprises, we can see that in all elements of time there are no significant deviations, the greatest being the degrees of machinery time $\bar{t}_{tm1} = 0.246$ and $\bar{t}_{tm2} = 0.2334$, followed by the degree of transport time $\bar{t}_{ur1} = 0.152$, while in the other enterprise this degree is significantly lower $\bar{t}_{ur2} = 0.0871$. The degrees of control time and packing time do not deviate significantly in the case of production time, while for non-production time in both enterprises the degree of other time is approximate to the sum of the other four $\bar{t}_{tto1} = 0.165$ and $\bar{t}_{tto2} = 0.1382$.

Taking these results into account the analysis should be directed towards the problem of transport time elements which might be reduced. The distribution of the time elements of other stoppages should be considered from a mathematical aspect so that the most significant elements within it are extinguished.

5. CONCLUSIONS

It has been proved that it is possible to master the process by applying a modified work sampling method for a corresponding representative set of working time elements, whose range along normal distribution law, dynamically viewed, is enabled using mean value calculations to establish control limits on three standard deviations for some individual working time elements.

Based on the theoretical postulates of the stochastic model used to determine the elements of PC time and the experimental evidence of the assumed model we infer that the PC is the most significant technical-technological indicator in production and it is necessary to steadily monitor and reduce it. Instead of the continuous screening and monitoring of working time elements in an analytical manner, monitoring is much simpler to perform by means of the original stochastic modified work sampling model, and PC reduction is possible by influencing the factors related to the duration of individual working time elements. Time elements trends can be mathematically monitored by establishing the control limits with $\pm$SD from the mean value. The PC mean value for the groups formed according to the number of units in a series (t_{pcu}) moves along the hyperbolic function which has asymptote c, $\bar{t}_{pcu} = c + b/n$, and, mathematically, these groups do not behave as strata, which means they are not linked to the deterministic factors of technology and the number of units/series. The process is mastered to a higher degree when all levels of working time elements are utilized to a higher degree (or %) and production time (t_p) is the most important for the process. This means that it is more favorable to apply higher organizational and production levels in the stochastic model for establishing the elements of PC time. In experiments to follow optimization is needed for the number of working time elements and stoppages depending on the production type. Future investigations should establish the characteristics of different types of production, such as the assembly processes in the textile industry and machine shops in the metalworking industry.

ACKNOWLEDGEMENT

This work was supported by the Serbian Ministry of Education and Science under Grant TR 35017.

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