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Management of technological process optimisation

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ABSTRACT

The research aims to characterise the optimisation of a technological process depending on the main time parameters for production. The optimisation does not require to correct technical parameters of a system, but rather the organisational and managerial factors of the technological process. The workload is taken as an evaluation criterion, which factors in the probability distribution of time characteristics of computer process operations. Time characteristics that represent the performance of an operation influence the workloads of an operator and equipment, determining the productivity of the technological process. Analytical models were developed for the operational control of a production line efficiency considering the probability–statistical parameters pertaining to the performance of operations and technological equipment peculiarities. The article presents research results, which characterise the dependence of a production line efficiency on the type of equipment, and the duration of preparatory and final operations considering their probability. Under an optimal workload of the operator, the duration of the complete program changes linearly, regardless of the time required for the performance of operations by a computer without the involvement of the operator, and depending on the type of equipment. A managerial decision can be optimal under the condition that the factor of technological process efficiency (K_TP) tends to max. The developed method of analytical determination can be used to calculate the workload of both an operator and technological equipment. The calculations of the duration of a production line operation resulted in the methodology for the consideration of probability characteristics pertaining to the time distribution of the period required to perform operations, which influences the unequal efficiency of the production line. The probabilistic character of time distribution related to intervals of performed operations serves as a parameter in the management of technological process optimisation, which can be achieved using simulators of technological processes optimised in terms of their efficiency.

KEY WORDS

workload factor, process productivity, analytical model, duration of operations, amount of equipment

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Introduction

The efficiency of modern automation of machine building is characterised by its flexibility, reduced production costs and the volume of manufactured products (Gálová et al., 2018). A technological process should result in a product of appropriate quality and low production cost within a short period (Sobolewski et al., 2012). This goal helps to increase competitiveness in the unstable economic market.

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Many approaches can be used to improve competitiveness. One of the concepts is flexible production. Flexibility depends on the probabilistic character of the performance of operations undertaken by an operator of technological equipment.

Thus, the duration of performing an operation will be different, as well as the workload of the equipment operator. The number of operations performed by one operator or certain equipment serviced by one operator depends on the duration of time required to perform the operations. It is important to exclude idle times of the operator and equipment.

The duration of time required for the performance of similar operations by various operators is different and accidental. The productivity of the technological process changes depending on the duration of performing an operation.

One possible way of optimisation is through the distribution of workstations (Kikolski et al., 2018). However, it is necessary to consider the duration of time required to perform the operation. Time is the main criterion, which influences productivity. The analysis of the duration of performing an operation characterises the functioning of a technological process (equipment). It optimises the amount of equipment serviced by one operator.

Thus, the actual problem is to develop a mathematic model to control the technological process optimisation, which does not require the correction of the system's technical parameters but rather of the organisational and managerial factors related to the technological process.

The duration of time required to perform operations is the main parameter, whereas the time of performance is accidental and probabilistic. The article presents the methodology of the research into an optimal amount of equipment serviced by one operator. The methodology considers the workload factor and the distribution of the duration of performing an operation, which corresponds to the law of normal distribution. The productivity of a technological line is the criterion of optimality.

The article presents research results regarding the duration of performing an operation using an example of a technological line in a machine-building company (Ukraine). The research was conducted using different combinations of workstations. Technological equipment was placed in a line, angle-wise to the direction of the operator's movement, i.e. the "herringbone" arrangement, or on both sides of the workstation of the operator, i.e. the "tandem" arrangement, or ordinarily, in the direction of the operator's movement, i.e. the "parallel" arrangement.

1. Literature Review

Optimisation is an instrument that can be used to solve engineering problems; however, it is not simple. No unified, universal method exists for an effective solution of engineering problems (Wędrychowicz & Bydałek, 2017). Recently, imitative modelling has become widely used. Application of an imitative model to a technological process of production based on standard stochastic distributions ensures the balancing between flows of production inputs and outputs considering the operator's workload (Rahman & Ullah, 2015; Zwierzyński et al., 2018). An imitative model is used to determine bottlenecks and evaluate some possible alternatives. For instance, the rearrangement of workstations or equipment, the adjustment of the level of resources, and the employment of additional workers. The research proposes alternative methods to increase the efficiency of the system under unset parameters and their limits, which optimise the technological process and, particularly, the productivity of the system.

Some researchers (Mourtzis et al., 2015; Al-Ahmari et al., 2016) consider that digital technologies of production can also be used to experiment with production systems and processes and production resources. However, such efforts are advisable at the level of abstracting and in the case of the lack of definite digital parameters for a technological process.

Technological process planning has changed together with the dynamic social demand, according to the Industry 4.0 concept (Briesemeister & Novaes, 2017). In particular, certain shifts occurred in logistic models of inputs and outputs of the production process. Traditionally, production is optimised based on a search with the help of a simulator to evaluate the importance of decisions (Ivanov, 2017; Ran, 2018).

The article offers a methodology for decision-making based on SPAF — the sustainable process analytics formalism (Shao et al., 2014). It provides step-by-step instructions including required data, sensitivity analysis and the optimisation of decisions in relation to sustainability indices on the basis of modelling and analysis. However, a mathematical model, either empirical or analytical, is the final element in decision-making.

The best possible decision suggests a dynamic optimisation of the technological process with the use of automatic systems of control in the case of a worker absence (Åkesson, 2008). Such a case requires a mathematical model and the specification of parameters.

Otherwise, it is required to use standard software programs, which ensure the assessment of decision-making risks on the basis of statistical data processing, while taking managerial actions to express the accepted optimisation parameter in qualitative terms (García & García, 2018; Sujová et al., 2019; Mourtzis, 2019; Kibira & Shao, 2016).

In contrast, mathematical and, particularly, analytical methods are universal and more available; besides, they secure effective decision-making. Explicit mathematical formulas and numerous methods of calculation are used. In such a case, modelling simulators are adjusted to specific conditions, performing faster and with high accuracy of optimisation and forecasting. Thus, analytical methods are still widely used for assessing the efficiency and production optimisation (Sujová et al., 2019; Mourtzis, 2019).

An analytical method has been developed to additionally consider the distribution of time intervals of an operation performed by an equipment operator. It determines the coefficient of the operator's workload, which indicates the amount of equipment that can be serviced by one operator effectively and immediately. The research considers different arrangements of equipment placed in a technological line and the movement of an operator from one piece of equipment to another while performing the same operations.

2. Research methods

2.1. Development of the method for the management of technological process optimisation

The control of efficiency of completed technological processes secures the continuous improvement of their operation in all fields, particularly, organisational, technological, economic and others (Tkaczyk & Roszak, 2002).

For a technological process, the efficiency of optimal functioning is assessed by the factor of efficiency K_{TP}:

$$K_{TP} = \frac{1}{C_{TP}} \sum_{n=1}^{i} \left(Q_P - \Delta Q_P\right), \tag{1}$$

where CTP stands for the consumption of energy required to perform the technological process;
Q_P — the productivity of a production process under ideal conditions;
ΔQ_P — the efficiency of a technological process under an inconsistency of the system's parameters, which are subordinate to the probability characteristic of the distribution of indices in time, revealed in their quantity equivalent, $\Delta Q_P = Q_P - W_{PTL}$;
W_{PTL} — productivity of the technological process considering the probability distribution of the duration of performing the operation.

The presented dependence (1) demonstrates that efficiency is contingent on parameters of a technical system, which should provide conditions for the performance of a technological process according to the technological requirements on the reduction of production costs.

The choice of a rational direction for the improvement of computer technology considering production peculiarities depends on requirements for technological operations of the production process. The efficiency can be increased by reducing the period of performance of some technological operations, which do not influence the quality of the final product.

A typical process of computer technology was taken as an example, the regulated workstations were subjected to a set of operations, performed by an operator according to the following technology:

- prepare to perform operations for a set of items:
  - the operator or an item approaches the device used to perform the operation;
  - preparatory operations (expected by regulations for the operation (route) map);
- performance of main operations:
  - switch on technological equipment operations and preliminary consistency control (position, supply, regimes, etc.);
  - perform main operations (under partial visual control by the operator);
- performance of final operations:
  - technical control of item parameters or other operations according to the operation (route) map;

– switch off the operation process and remove the item off of the equipment;
– control the conditions, move to the next operation or item.

To make a theoretical analysis into the regularities of technological indices of the process, depending on the type of technological equipment (manual, automatic, robotised), standard consumption of time can be used for the performance of an operation or the consumption of time by the stopwatch study.

The duration of time required to perform main operations is regulated by the operation modes of technological equipment and by the item, which is processed by the equipment.

The productivity and efficiency of work of an operator manning the technological equipment (tools) and the quality of performed operations (according to standard requirements) depend on the amount of servicing equipment, simultaneously controlled by one operator. The amount of servicing equipment, simultaneously maintained by one operator, depends on the time of performance of the main operation (without the operator's participation, but performed by equipment, programmed by the operator, to complete one operation) and the duration of preparatory and final operations, and the time required for passing from one equipment to another (or a workstation).

The visualise how a technological process is organised using the technological equipment as well as understand the sequence of operations performed by the operator, Fig. 1 presents a cycle scheme of the stream process used by computer technology of a random performed operation.

For instance, if one operator services four workstations, where each of the stations has two operations equal in time, the operator performs the first operation and then passes to the second. Thus, having four workstations, the operator controls four technological machines or one operation in each, i.e. the number of simultaneously processed items (details, etc.).

Fig. 1 demonstrates that having an optimal number of workstations or an amount of serviced equipment per one operator, the factor of the operator workload should be equal to one or approaching one.

The duration of preparatory and final operations depends on the conformity with standard requirements and technological skills (qualification) of the operator. Considering the sequence of preparatory and final operations of computer technology (Fig. 1), the factor of the operator workload K_{op} is calculated by the formula (Dmytriv et al., 2018):

$$K_{op} = \frac{t_{sdo} + (n_{am.ed} - 1) \cdot t_f}{n_{am.ed} \cdot t_{p-f}}, \qquad (2)$$

where t_{sdo} stands for the duration of operations on one equipment or one workstation, $t_{sdo} = t_m + t_{p\text{-}f}$, s;
t_m — the duration of operation performed immediately on the equipment, without the operator's participation, s;
t_f — the duration of final operations, s;
$t_{p\text{-}f}$ — the duration of preparatory and final operations, s;
$n_{am.ed}$ — the amount of equipment, controlled by one operator, or the number of workstations serviced by one operator, units.

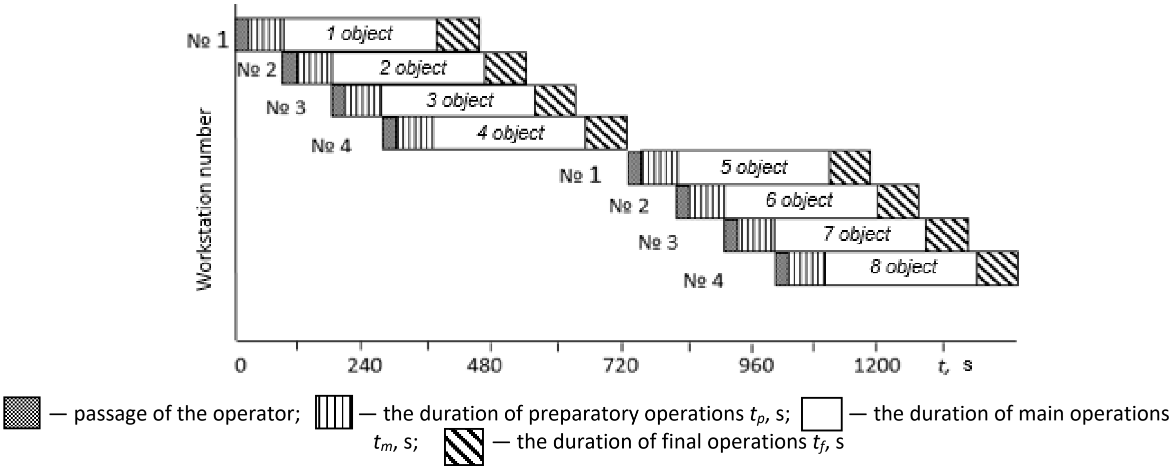


Fig. 1. Cycle scheme of computer technology

If $K_{op}>1$, the operator is underloaded and has free time, whereas if $K_{op}<1$, the operator is overloaded and does not keep to performance regulations regarding preparatory and final operations due to the lack of time.

Considering that $t_{p\text{-}f} = t_p + t_f$, $t_{sdo} = t_p + t_m + t_f$ and using the dependence (2) for the calculation of the optimal amount of technological equipment per one operator, the following result is obtained:

$$n_{am.ed} = \frac{t_m}{t_p} \cdot \left[K_{op} + \frac{t_f}{t_p}(K_{op}-1) \right]^{-1} + \left[K_{op} + \frac{t_f}{t_p}(K_{op}-1) \right]^{-1} \quad (3)$$

$$\text{or} \quad n_{am.ed} = \left[K_{op} + \frac{t_f}{t_p}(K_{op}-1) \right]^{-1} \cdot \left[\frac{t_f}{t_p} + 1 \right] \quad (4)$$

where t_p stands for the performance of preparatory operations by the operator, s.

Considering the mathematical model for the probability of performance of operations by computer technologies, the impact of the process design for different types of technological equipment (manual, automatic, robotised) on the distribution of time intervals representing the duration of performed preparatory and finishing operations is analysed in the research. The indices used to organise the technological process of the equipment operator include productive efficiency of the operator and equipment; and the probable and mathematical expectation for the duration of preparatory and finishing operations.

The law of normal distribution applies to the duration of time required to perform preparatory and finishing operations by computer technologies, their limits of the scope, the mean square deviation, and dispersion of the results for a sampling distribution of 100 observations of the performance of operations using different types of technological equipment (Kodra et al., 2008).

The distribution of the duration of time required to perform preparatory and finishing operations is subordinate to the normal law, which is characterised by the probability density function (Bronstein et al., 1986):

$$f(t) = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \mathrm{e}^{-\frac{(t-m(\bar{t}))^2}{2 \cdot \sigma^2}}, \quad (5)$$

where σ stands for a confidence interval; $m(\bar{t})$ mathematical expectation.

A mathematical expectation of the variable t for the Gaussian distribution is determined by the formula (Bronstein et al., 1986):

$$M|t| = \int_{-\infty}^{\infty} t \cdot f(t) \cdot dt = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \int_{-\infty}^{\infty} t \cdot \mathrm{e}^{-\frac{(t-m(\bar{t}))^2}{2 \cdot \sigma^2}} \cdot dt \quad (6)$$

The $\frac{t-m(\bar{t})}{\sigma \cdot \sqrt{2}} = x$ is substituted for the integration of equation (6). Consequently, equation (6) undertakes the following form:

$$M[t] = \frac{1}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} \left(\sigma \cdot x \cdot \sqrt{2} + m(\bar{t}) \right) \cdot \mathrm{e}^{-x^2} \cdot dx = = \frac{\sigma \cdot \sqrt{2}}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} x \cdot \mathrm{e}^{-x^2} \cdot dx + \frac{m(\bar{t})}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} \mathrm{e}^{-x^2} \cdot dx. \quad (7)$$

In equation (7), the first integral is equal to zero, and the second is the Euler–Poisson integral, respectively:

$$\int_{-\infty}^{\infty} \mathrm{e}^{-x^2} \cdot dx = 2 \int_{0}^{\infty} \mathrm{e}^{-x^2} \cdot dx = \sqrt{\pi}. \quad (8)$$

Thus $M|t| = m(\bar{t})$ which characterises the mathematical expectation of the variable t, is the average value for the integral of distribution of the random variable t.

The dispersion of the variable t is calculated by the formula (Bronstein et al., 1986):

$$D|t| = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot \int_{-\infty}^{\infty} \left(t - m(\bar{t}) \right)^2 \cdot \mathrm{e}^{-\frac{(t-m(\bar{t}))^2}{2 \cdot \sigma^2}} \cdot dt \quad (9)$$

The $\frac{t-m(\bar{t})}{\sigma \cdot \sqrt{2}} = x$ is substituted, and, consequently, equation (9) undertakes the following form:

$$D|x| = \frac{2 \cdot \sigma^2}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} x^2 \cdot \mathrm{e}^{-x^2} \cdot dx \quad (10)$$

The integration of parts of equation (10) resulted in the following equation:

$$D|x| = \frac{2 \cdot \sigma^2}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} x^2 \cdot \mathrm{e}^{-x^2} \cdot dx = \frac{\sigma^2}{\sqrt{\pi}} \cdot \int_{-\infty}^{\infty} 2 \cdot x \cdot x \cdot \mathrm{e}^{-x^2} \cdot dx = = \frac{\sigma^2}{\sqrt{\pi}} \cdot \left\{ -x \cdot \mathrm{e}^{-x^2} \Big|_{-\infty}^{\infty} + \int_{-\infty}^{\infty} \mathrm{e}^{-x^2} \cdot dx \right\}. \quad (11)$$

The first addition of integral (11) under $x \to \infty$ is reduced faster than the exponentiation growth. Thus, it is equal to zero. The second addition of integral (11) is equal to $\sqrt{\pi}$, according to the dependence (8).

Thus, the dispersion of the variable t will be $D|t| = \sigma^2$, and σ in equation (5) is a mean square deviation S of the variable t.

Table 1 presents the distribution of performance duration of preparatory and final operations for the set types of technological equipment, as well as their mathematical expectation and dispersion.

Using the distribution model for the duration of preparatory and final operations and having a mathematical expectation regarding the duration of the performance of those operations (Table 1), the model is created for the duration of the performance

Tab. 1. Characteristics pertaining to the distribution of the duration of preparatory and final operations performed by computer technology

Type of technological equipment	Operations	Distribution law	Mathematical expectation $M(T_P)$, $M(T_F)$, s	Mean square deviation S, dispersion Σ^2
Manual, linear arrangement	t_p	$f(t_p)=\frac{1}{8,225\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_p-67,79)^2}{2\cdot 67,65}}$	$M(t_p)$=67.79±8.225	$S(t_p)$ = 8.225 σ^2 = 67.65
	t_f	$f(t_f)=\frac{1}{14,12\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-82,02)^2}{2\cdot 199,38}}$	$M(t_f)$=82.02±14.12	$S(t_f)$ = 14.12 σ^2 = 199.379
Partially automated, linear arrangement	t_p	$f(t_p)=\frac{1}{8,233\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_p-68,65)^2}{2\cdot 67,78}}$	$M(t_p)$=68.65±8.233	$S(t_p)$ = 8.233 σ^2 = 67.78
	t_f	$f(t_f)=\frac{1}{10,22\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-53,11)^2}{2\cdot 104,44}}$	$M(t_f)$=53.11±10.22	$S(t_f)$= 10.219 σ^2 = 104.438
Partially automated, "tandem" arrangement	t_p	$f(t_p)=\frac{1}{4,431\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_p-36,84)^2}{2\cdot 19,634}}$	$M(t_p)$=36.84±4.431	$S(t_p)$ = 4.431 σ^2 = 19.634
	t_f	$f(t_f)=\frac{1}{4,432\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-45,34)^2}{2\cdot 19,64}}$	$M(t_f)$=45.34±4.432	$S(t_f)$ = 4.432 σ^2 = 19.644
Automatic, "tandem" arrangement	t_p	$f(t_p)=\frac{1}{4,627\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_p-37,85)^2}{2\cdot 21,41}}$	$M(t_p)$=37.85±4.627	$S(t_p)$ = 4.627 σ^2 = 21.41
	t_f	$f(t_f)=\frac{1}{2,43\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-17,61)^2}{2\cdot 5,898}}$	$M(t_f)$=17.61±2.429	$S(t_f)$ = 2.429 σ^2 = 5.898
Automatic, "herringbone" arrangement	t_p	$f(t_p)=\frac{1}{2,99\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-38,29)^2}{2\cdot 8,926}}$	$M(t_p)$=38.29±8.926	$S(t_p)$ = 2.987 σ^2 = 8.926
	t_f	$f(t_f)=\frac{1}{0,48\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-10,1)^2}{2\cdot 0,23}}$	$M(t_f)$=10.1±0.48	$S(t_f)$ = 0.48 σ^2 = 0.23
Automatic, "parallel" arrangement	t_p	$f(t_p)=\frac{1}{3,94\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_p-31,09)^2}{2\cdot 15,522}}$	$M(t_p)$=31.09±3.94	$S(t_p)$ = 3.94 σ^2 = 15.522
	t_f	$f(t_f)=\frac{1}{0,904\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{(t_f-10,94)^2}{2\cdot 0,816}}$	$M(t_f)$=10.94±0.904	$S(t_f)$= 0,904 σ^2 = 0.816

of one-type operation using different types of technological equipment. From equation (2), it is possible to derive a dependence for the calculation of the duration of an operator workload by the calculated amount of technological equipment. The duration of the operator workload depending on the amount of manned equipment can be calculated by the formula:

$$t_w = K_{op}\cdot n_{am.ed}\cdot(t_p + t_f) \qquad (12)$$

Due to the probabilistic character of the distribution representing the duration of the performance of preparatory and final operations, dependence (12) undertakes the following form considering the mathematical expectation for the performance of operations:

$$t_w = K_{op}\cdot n_{am.ed}\cdot\left[\bar{t}_p \pm S(t_p) + \bar{t}_f \pm S(t_f)\right], \qquad (13)$$

where $\bar{t}_p, \bar{t}_f$ stands for the average value of the duration of preparatory and final operations, respectively, s;

$S(t_p), S(t_f)$ — the mean square deviation of the duration of preparatory and final operations performed by computer technology, respectively, s.

The duration of the performance of a production program considering the number of operators per computer technology (workstations or technological equipment) is calculated by the formula:

$$T_w = K_{op}\cdot n_{am.ed}\cdot\left[\bar{t}_p \pm S(t_p) + \bar{t}_f \pm S(t_f)\right]\cdot M_{prog}/N_{n.op}, \qquad (14)$$

where $M_{прог}$ stands for the production program, units; $N_{оп}$ — the number of operators, servicing a technological line, number of people.

Dependence (14) enables calculating the duration of the performance of a program with different duration of the performance of an operation immediately on the equipment and without the operator's participation, and the optimal workload for different types of technological equipment.

2.2. Model of a technological process efficiency under the rational workload of a computer technology operator

The productivity of different types of technological equipment used for operations of different duration to procedure one item ensures the optimised management of the technological process.

Considering the duration of the operations t_{sdo} for one production item (considering the performance of preparatory and final operations $t_{sdo} = t_m + t_{p\text{-}f}$), the dependence for the determination of labour efficiency will have the following form:

$$W_{op} = \frac{3600 \cdot n_{am.ed}}{t_{sdo}}. \quad (15)$$

From dependence (2), the dependence can be derived for the operator efficiency or the efficiency of a production line with a set amount $n_{am.ed}$ of technological equipment, having determined the duration of the operations t_{sdo} for each production item and having introduced it in dependence (15):

$$W_{PTL} = \frac{3600 \cdot n_{am.ed}}{K_{op} \cdot n_{am.ed} \cdot (t_p + t_f) + t_f (1 - n_{am.ed})}. \quad (16)$$

Considering the mathematical expectation for the duration of time required to perform preparatory and final operations, dependence (16) undertakes the following form:

$$W_{PTL} = \frac{3600 \cdot n_{am.ed}}{K_{op} \cdot n_{am.ed} \cdot \left[\bar{t}_p \pm S(t_p) + \bar{t}_f \pm S(t_f)\right] + \left(\bar{t}_f \pm S(t_f)\right) \cdot (1 - n_{am.ed})}. \quad (17)$$

With the help of the developed analytical method, the research was conducted, which confirmed the reasonability to use the statistical distribution of probability for the duration of operations performed by an operator for the management of the technological process optimisation.

3. Research results

3.1. Results of the analytical research of an operator's workload

The amount of equipment serviced by one operator characterises the workload. Results of the modelling of the operator workload and dependence (2) are demonstrated in Figs. 2–4.

The increase in the amount of equipment, which is serviced by one operator (Figs. 2 and 3), causes an increase in the operator's workload. Thus, the operator cannot keep to the set time limits required to perform the operation adequately. Therefore, the coefficient of the operator's workload depends on the correlation between the duration of the performance of the operation immediately by the operator and the duration of the performance of operations without the operator's participation.

Results of the modelling for the optimal amount of technological equipment per one operator are demonstrated in Fig. 5.

Under the condition that final operations are performed without the participation of an operator (i.e. automated or serviced by a robot), the change of t_f/t_p correlations from 1 to 7 contributes to a significant increase in the amount of equipment serviced by one operator. For the analysis of dependence (4), the article supplies a diagram of the response projections (Fig. 6).

The duration tm of an operation performed immediately on the equipment without the operator's participation is an important parameter influencing the amount of equipment, which is simultaneously serviced by the operator. The analysis of the graphical dependences (Figs. 5 and 6) resulted in a sampling of the most common types of equipment used in Ukraine (Fig. 7).

The analysis of the research results (Figs. 5 and 6) demonstrated that an increase in the duration of computer operations (t_m) without the operator's participation led to an increase in the amount of equipment serviced by one operator. Similarly, an increase in the correlation between the finishing and preparatory operations caused an increase in the amount of equipment serviced by one operator.

The condition for the conformity of the operator's work with requirements of computer technology is expressed as $Kop \geq 1$.

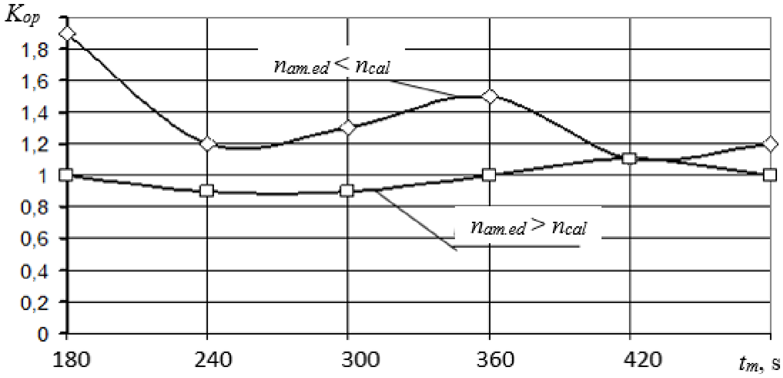


Fig. 2. Workload of the operator of manual technological equipment

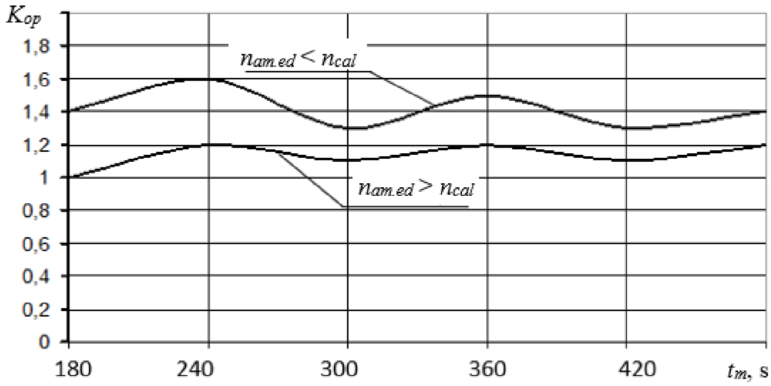
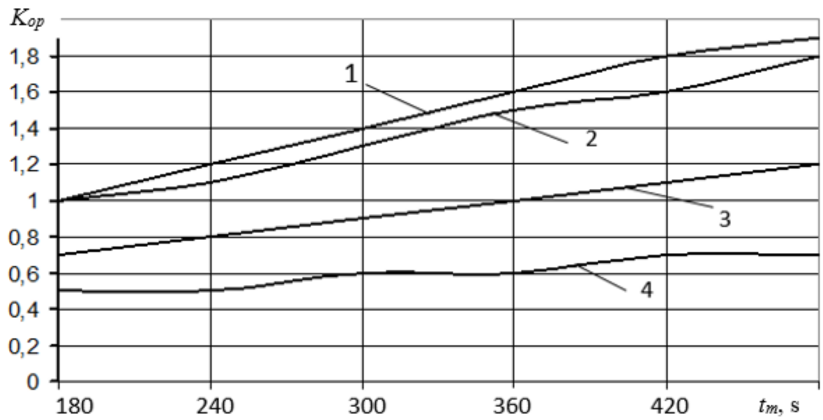


Fig. 3. Workload of the operator of partially automated technological equipment



1 — partially automated, "herringbone" arrangement, 4 units of equipment; 2 — partially automated, "tandem arrangement, 3 units of equipment; 3 — automatic, "herringbone" arrangement, 8 units of equipment; 4 — automatic, "herringbone" arrangement, 16 units of equipment

Fig. 4. Workload of the operator of automated technological equipment

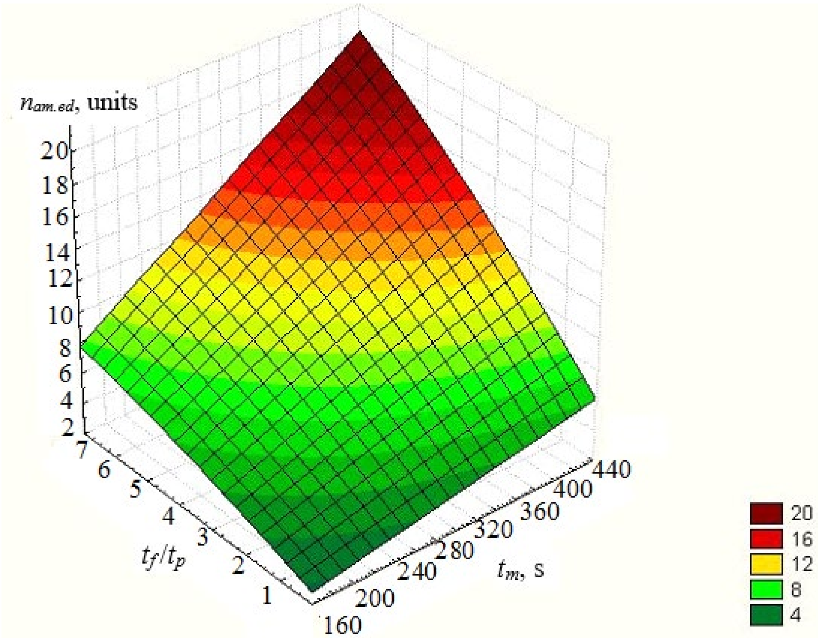


Fig. 5. Dependence of the amount of technological equipment $n_{am.ed}$ serviced by one operator on the duration t_m of the operation performed immediately on the equipment and without the operator's participation and the correlation of final and preparatory operations t_f/t_p

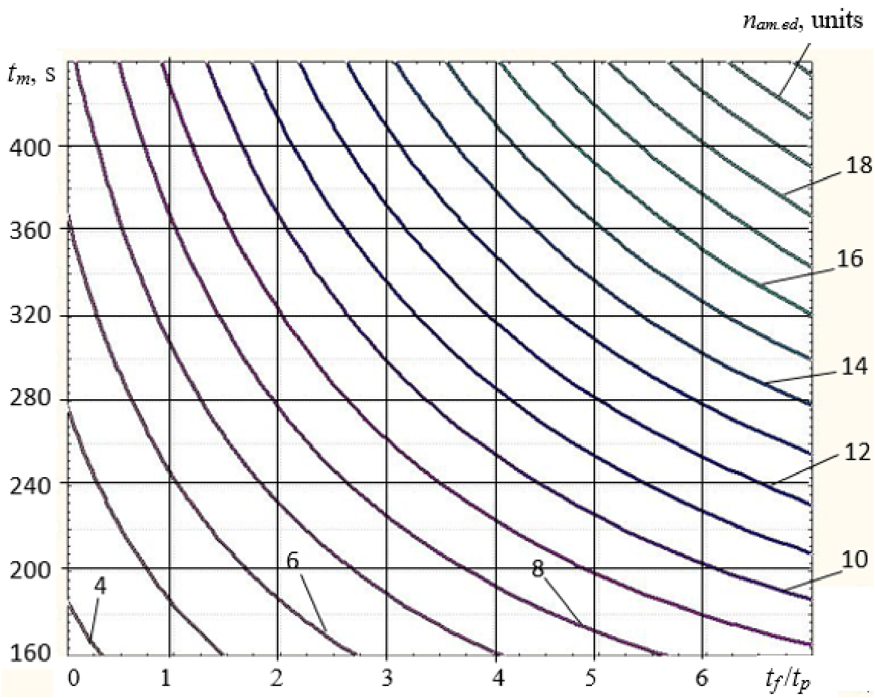
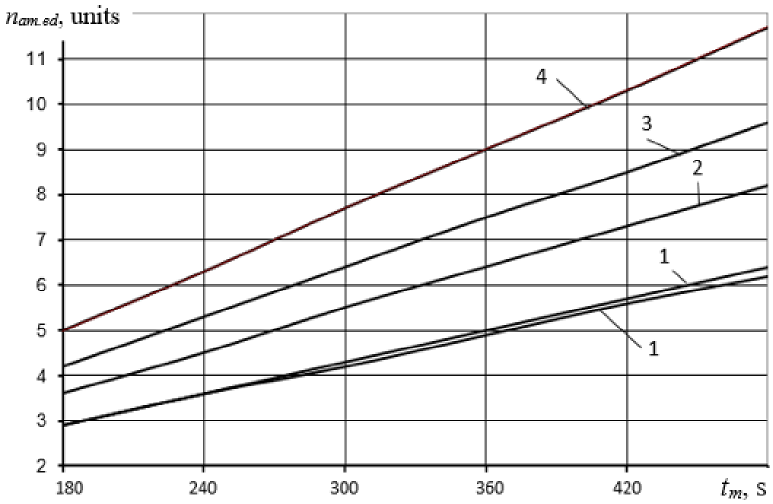


Fig. 6. Diagram of projections for the response surface of a dependence of the amount of equipment $n_{am.ed}$ serviced by one operator on the performance duration t_m of the operation immediately on the equipment and without the operator's participation and the correlation of final and preparatory operations t_f/t_p



1 — manual, linear arrangement; 2 — partially automated, linear arrangement; 3 — automatic, t_f/t_p ɜm” arrangement; 4 — automatic, “herringbone” arrangement

Fig. 7. Dependence of the amount of technological equipment $n_{am.ed}$ serviced by one operator on the duration t_m on of the operation performed immediately on the equipment and without the operator’s participation, and on the type of equipment

Thus, an increase in the level of automation of technological operations ensures an increase in the amount of equipment serviced by one operator (Fig. 7). The duration of computer operations, regardless of the level of automation, leads to an increase in the amount of equipment serviced by one operator.

3.2. Results of the analytical research on the duration of work and efficiency of a production line

Figs. 8–11 present the calculations for the duration required to perform a program using dependence (13) and different duration of the operation performed immediately on the equipment without the operator’s participation and the optimal workload of the operator for different types of technological equipment.

The reduction in the duration of a production line operation within the range of the correlation $t_f/t_p = 0.5\text{-}0.8$ results from the optimal amount of technological equipment serviced by one operator, and under $K_{op} \approx 1$. The reduction in $K_{op}<1$ is intolerable because the operator will not manage to perform all operations according to requirements because of the unargued amount of serviced technological equipment.

The productivity of a production line (equation 21) depends on the duration of time required to perform preparatory tp and final tf operations, which have the number series subordinate to the normal distribution and the duration tm of performance of the computer operations without operator’s participation. It also characterises the number of equipment units serviced by an operator and regulates the factor of the operator workload Kop. The modelling results are demonstrated in Fig. 12.

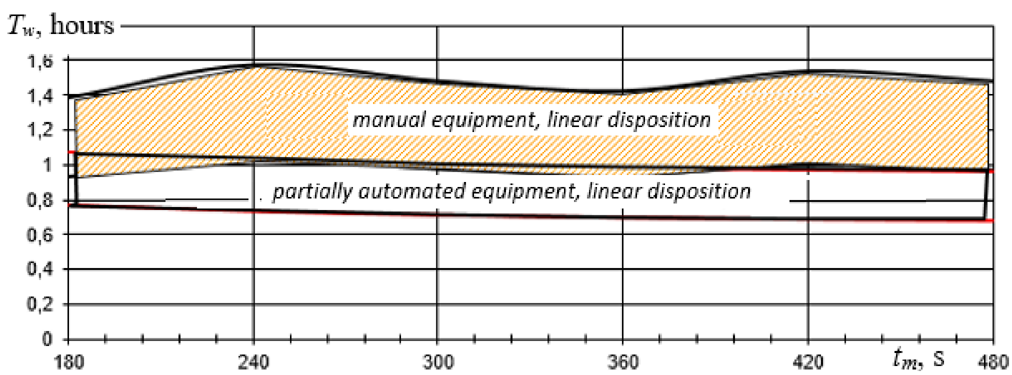


Fig. 8. Interval in the duration of a production line operation to perform the program for 100 products during the time t_m of the operation performed immediately on the equipment and without the participation of the operator

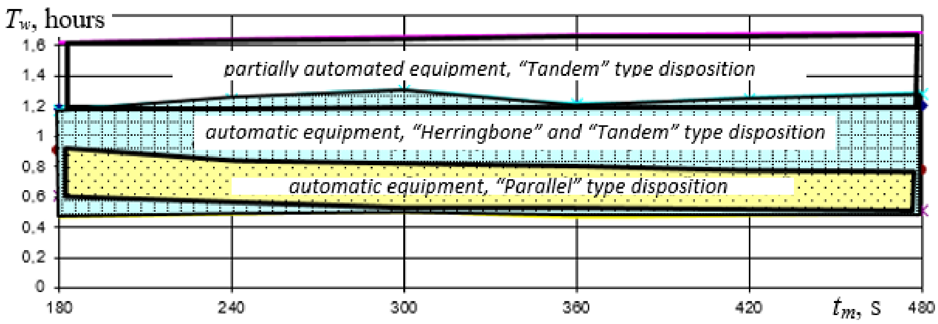


Fig. 9. Interval in the duration of a production line operation to perform the program for 100 products during the time t_m of the operation performed immediately on the equipment and without the participation of the operator

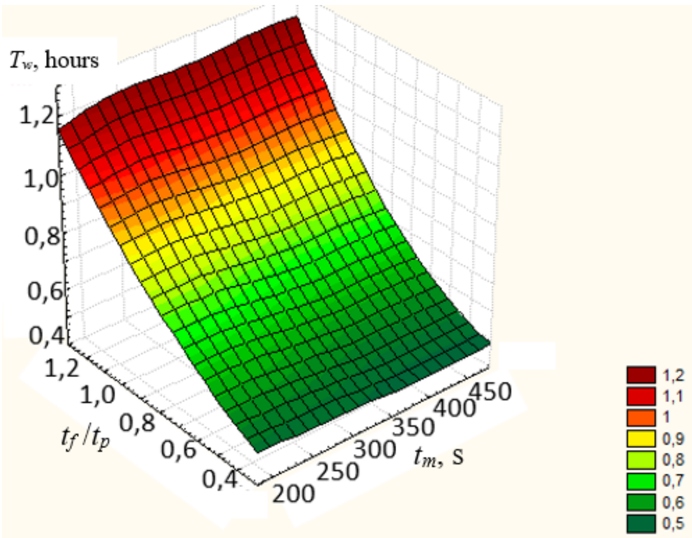


Fig. 10. Dependence of the duration of a production line operation to perform the program for 100 products during the time t_m of the operation performed immediately on the equipment and without the participation of the operator, and the correlation t_f/t_p, under: $t_f \to min$, $t_p \to min$

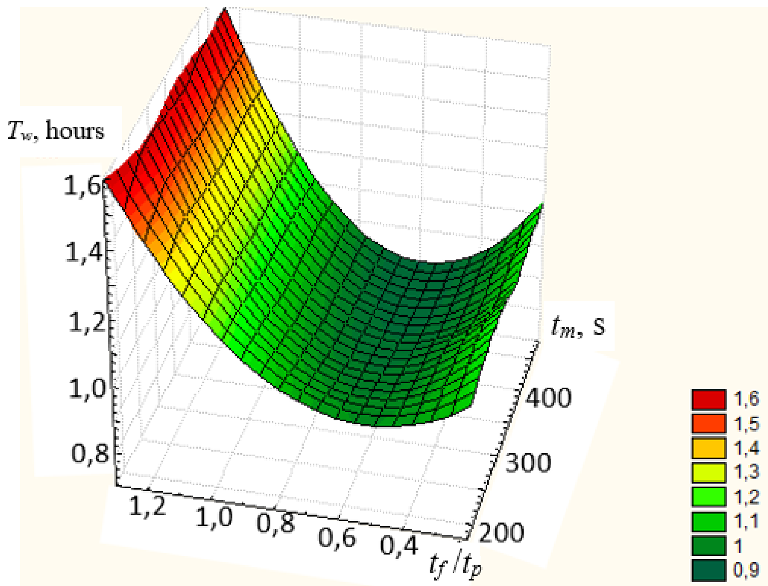


Fig. 11. Dependence of the duration of a production line operation to perform the program for 100 products during the time t_m of the operation performed immediately on the equipment and without the participation of the operator, and the correlation t_f/t_p, under: $t_f \to max$, $t_p \to max$

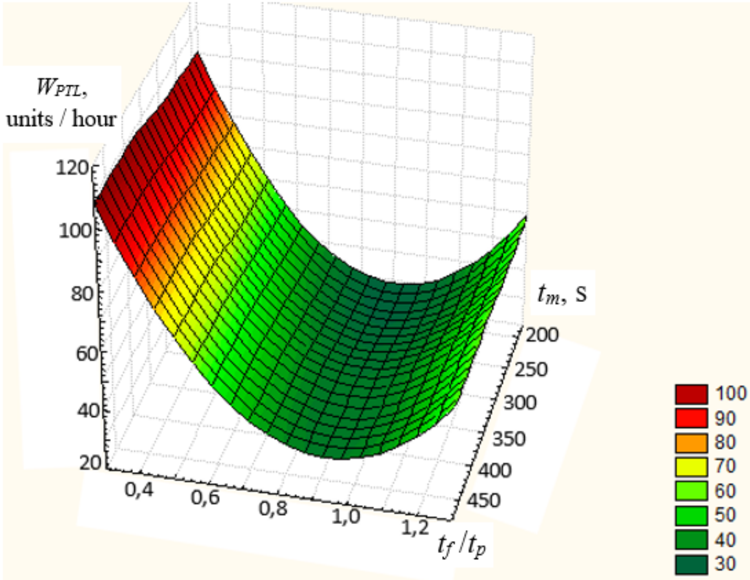


Fig. 12. Dependence of the efficiency of technological equipment on the duration t_m of the operation performed immediately on the equipment and without the participation of the operator, and on the correlation t_f/t_p, under: $t_f \rightarrow min$, $t_p \rightarrow min$

4. Discussion of the results

The analysis of modelling results demonstrated that under the optimal workload of an operator ($1.0 \leq K_{op} < 1.15$), the duration of time required to perform the program changes linearly, regardless of the time tm of the operation performed immediately and without the participation of the operator, and depends on the type of equipment (Figs. 10 and 11).

The analysis into the dependence of the efficiency of technological equipment on the duration tm of operations performed by computer without the participation of an operator, and the correlation t_f/t_p under $t_f \rightarrow min$, $t_p \rightarrow min$ (Fig. 12) confirmed that the productive efficiency of equipment is subordinate to the second-order equation. In the 3D diagram (Fig. 12), the domain of the efficiency of a technological process at the level of 29–36 unit/hour corresponds to the manual equipment with a linear arrangement, and 51 unit/hour or more — the automatic equipment with the arrangement, which is required for the work of manipulation robots.

Therefore, the results of the research on the dependence of the efficiency of a production line on time characteristics of the technological process can be used to optimise the process control by determining the efficiency of the optimal operation by expression (1).

The reduction in losses of a technological process efficiency causes an increase in system efficiency.

Conclusions

The analysis into a technological process of computer technologies demonstrated that the duration of preparatory and final operations depended on the type of equipment, level of automation of operations and instruments, and partially depended on an operator's qualification and sense of responsibility.

The amount of technological equipment serviced by one operator characterises the workload under the condition of the conformity with standard requirements for computer technology.

The time interval of the technological equipment operation depends on intervals of preparatory and final operations and the time tм of the operation performed immediately on the equipment and without the operator's participation. Thus, when the factor Kop of the operator's workload approaches one, the duration of the equipment operation reduces. However, in the case of increasing $K_{op} > 1$, the operator will be underloaded, and thus, the duration of the technological equipment operation will increase.

The optimality of the approved managerial decision is reached under the condition when $K_{TP} \rightarrow max$.

The developed method for the analytical determination of the workload helps to calculate the workloads of an operator and technological equipment. The calculations of the duration of a production line operation resulted in the methodology for the consideration of probability characteristics pertaining to the time distribution of the period required to perform operations, expressed a the irregularity of the production line efficiency.

The consideration of the probabilistic character of distribution of time intervals required to perform an operation is taken as a parameter for the management of a technological process optimisation, which can be achieved using simulators of technological processes with optimised efficiency.

Literature

Åkesson, J. (2008). *Optimica - An Extension of Modelica Supporting Dynamic Optimization*. Paper presented at 6th International Modelica Conference, Bielefeld, Germany, 57-66. Retrieved from https:// portal.research.lu.se/portal/files/6062979/8253707.pdf

Al-Ahmari, A., Abidi, M., Ahmad, A., & Darmoul, S. (2016). Development of a virtual manufacturing assembly simulation system. *Advances in Mechanical Engineering*, *8*(3), 1-13. doi: 10.1177/1687814016639824.

Briesemeister, R., & Novaes, A. (2017). Comparing an approximate queuing approach with simulation for the solution of a cross-docking problem. *Journal of Applied Mathematics*, *6*, 1-11. doi: 10.1155/2017/4987127

Bronstein, I. N., & Semendiaiev, K. A. (1986). *Guide on mathematics for engineers and students of higher education establishments*. Moscow, Russia: Nauka.

Dmytriv, V., Dmytriv, I., Lavryk, Y., & Horodeckyy, I. (2018). Models of adaptation of the milking machines systems. Contemporary Research Trends in Agricultural Engineering. *BIO Web of Conferences*, *10*, 02004. doi:10.1051/bioconf/20181002004

Gálová, K., Rajnoha, R., & Ondra, P. (2018). The Use Of Industrial Lean Management Methods In The Economics Practice: An Empirical Study Of The Production Companies In The Czech Republic. *Polish Journal of Management Studies*, *17*(1), 93-104.

García, S. G., & García, M. G. (2018). Design and Simulation of Production and Maintenance Management Applying the Viable System Model: The Case of an OEM Plant. *Materials*, *11*, 1346. doi:10.3390/ma11081346

Ivanov, D. (2017). *Operations and supply chain simulation with AnyLogic*. Decision-oriented introductory notes for master students. Berlin School of Economics and Law. Retrieved from https://www.anylogic.com/ upload/pdf/Ivanov_AL_book_2017.pdf

Kibira, D., & Shao, G. (2016). *Virtual Factory Framework for Supporting Production Planning and Control*. Conference Paper in IFIP Advances in Information and Communication Technology. doi: 10.1007/978-3-319-51133-7_35

Kikolski M. & Ko C-H. (2018). Facility layout design – review of current research directions. *Engineering Management in Production and Services, 10*(3), 70-79. doi: 10.2478/emj-2018-0018

Kodra, Yu. V., Stotsko, Z. A., & Havrylchenko, O. V. (2008). *Loading devices of technological machines. Calculation and construction. Manual.* Lviv, Ukraine: Publishing house "Beskyd Bit".

Mourtzis, D. (2019). Simulation in the design and operation of manufacturing systems: state of the art and new trends. *International Journal of Production Research*, *58*(7), 1927-1949. doi: 10.1080/00207543.2019.1636321

Mourtzis, D., Papakostas, N., Mavrikios, D., Makris, S., & Alexopoulos, K. (2015). The Role of Simulation In Digital Manufacturing – Applications And Outlook. *International Journal of Computer Integrated Manufacturing*, *28*(1), 3-24. doi: 10.1080/0951192X.2013.800234

Rahman, Ch., & Ullah, S. (2015). Process Flow Improvement Proposal of a Batch Manufacturing System Using ARENA Simulation Modeling. *Review of General Management*, *21*(1), 63-77.

Ran, L., Xiaolei, X., Kaiye, Y., & Qiaoyu, H. (2018). A survey on simulation optimization for the manufacturing system operation. *International Journal of Modelling and Simulation*, *38*(2), 116-127. doi: 10.1080/02286203.2017.1401418

Shao, G., Brodsky, A., Shin, S.-J., & Kim, D. B. (2014). Decision guidance methodology for sustainable manufacturing using process analytics formalism. *Journal of Intelligent Manufacturing*, *28*(2), 455-472. doi: 10.1007/s10845-014-0995-3

Sobolewski, J. (red.), Sieminski, P., & Sobieszczanski, J. (2012). *Technologies of production and projection of technological processes*. Warsaw, Poland: Politechnika Warszawska.

Sujová, E., Cierna, H., & Bambura, R. (2019). *Simulation model of production as tool for industry 4.0 implementation into practice*. 18-th International Scientific Conference Engineering for Rural Development. doi: 10.22616/ERDev2019.18.N279

Tkaczyk, S., & Roszak, M. (2002). *Analysis of the technological process based on the added value criterion.* 11 International Conference AMME'2002, Gliwice-Zakopane. Retrieved from http://www.journalamme.org/ papers_ amme02/11121 .pdf

Wędrychowicz, M., & Bydałek, A. (2017). Optimization of the production process of "Glogow II" melting with application of technological supplement CaF2. *Methods and Instruments of Production Technique, 2*, 123-132.

Zwierzyński, P., & Ahmad, H. (2018). Seru production as an alternative to a traditional assembly line. *Engineering Management in Production and Services, 10*(3), 62-69. doi: 10.2478/emj-2018-0017