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# INDUSTRIAL MACHINE AND PRODUCTIVITY OF AUTOMATED LINES

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## ABSTRACT

The contribution of this paper is the development of analytical equations for calculation of the availability of a machine and its productivity as a function of standard indices of reliability and technical parameters of a machine. The reliability of industrial machines with complex design like automated lines also depends on structural and technical data. The equations of productivity rate with availability allow the output of the automated lines to be modelled and their structures to be defined according to the level of productivity and reliability as a function of technical and technological parameters of industrial machines with complex designs.

**KEYWORDS**: reliability, indices, industrial machines.

## INTRODUCTION

There are many publications which describe the productivity and availability of flow manufacturing lines with independent working machines using a probabilistic approach [4–6]. Finally, the results of the probabilistic approach allow calculation of average magnitudes of searching parameters. Other publications are dedicated to studying the work and productivity of automated lines with buffers for different processing times of stations. These publications do not consider indices of reliability like failure rate and mean repair time of machine units and stations and do not show dependencies of the productivity of machines with a multi-parametrical nature of functioning.

One of the main indices of machine efficiency is the productivity rate, which depends on the reliability of a machine and its quality of exploitation. The productivity of a machine has a direct relationship with its reliability and it can be described analytically. The theory of reliability gives standard indices and modes of calculation of the reliability for complex systems. However, known indices and formulas of the machine reliability describe the machine productivity rate and its structure separately [5,6]. Mathematical expressions of machine productivity make it possible to include standard indices of reliability as components of equations of the productivity rate for different designs and structures of machines [7]. Also, analytical investigations show that the main index of reliability of industrial machines with complex design includes standard indices of reliability and the indices of the structure of machines. The main index of reliability of machines includes standard indices of reliability and indices of structural design of machines.

The real industrial environment shows that machinery sometimes experiences unpredictable failures for different reasons, especially automated lines with complex designs that have many mechanical, electrical, and electronic units of different levels of reliability. The reliability level of machinery with complex designs is evaluated by methods of the theory of reliability.

Generally, the index of productivity of machines is complex and includes technological, technical, reliability, structural, service, and organizational parameters. For analysis and synthesis of engineering solutions, researchers should present analytical dependencies for evaluation of machinery according to a productivity criterion which includes all components of the design of machines and manufacturing process.
Otherwise the efficiency of machines, which is calculated according to reliability, stresses, kinematics, dynamics, accuracy, and so on, is deemed useless. It means industrial machines of low productivity are not effective and not profitable for companies. Manufacturers are always striving and

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struggling for high productivity and quality of machined parts.

All indices of reliability of machines are classified into two groups: single indices that characterize one aspect of machine failures, and indices of reliability that include several single indices of reliability of a machine. The theory of reliability gives standard indices of reliability for reparable machines, of which one is availability, the main index of reliability of a system that is presented by the formula:

$$A = \frac{T_0}{T_0 + T} \ , \qquad (1)$$

where A is the availability of a machine, $T_0$ is the time that the machine works, and $T_i$ is the time that machines do not work, including repair and maintenance time.

The index of availability is used for machines when the consequences of random failure only lead to economic losses, like loss of productivity rate, and so on. Availability is expressed by the machine failure rate $\lambda = 1/m_w$, or the mean time between failures $m_w$ (MTBF), and mean repair time $m_r$ (MTTR) by the following expression:

$$A = \frac{m_w}{m_w + m_r} = \frac{1}{1 + m_r \lambda} \qquad (2)$$

These indices of the machine reliability will be used to develop analytical dependencies of the productivity rate as a function of reliability and structural parameters of a complex design machine. Industrial machines with complex designs like automated lines can have different structures that include a number of serial or parallel stations embedded in automated lines, and a number of sections of automated lines with buffers of different capacities.

The known equations of the productivity rate for different designs of machines include technological parameters (machining time that depends on processing mode), technical parameters (auxiliary time, capacity of buffers, etc.), and structural parameters (number of serial and parallel stations and number of sections of automated lines) [7–10]. Also, equations include reliability components, which are presented by expressions of machine idle time and can be converted to standard indices of reliability.

Preliminary analysis of equations of automated lines productivity shows that reliability components include machine failure rate, mean time to failure, mean time to repair, and availability. These indices of reliability in equations of the machine productivity rate can be analytically combined and presented in the form of the integrated index of reliability for different types of automated lines. This index of reliability for automated lines includes the structure of lines and capacity of buffers, apart from indices of reliability, that is, the structure and buffer capacities influence the reliability level and hence the productivity rate of automated lines.

## ANALYTICAL APPROACH

The term "productivity of machines" includes all aspects of the manufacturing processes, that is, technological, which means machining modes, and technical, which means the design and structure of machines, management, maintenance, and so on. Equations of productivity rate of industrial machines represent analytical dependencies of the productivity on the level of consideration of the manufacturing processes. There are equations that consider some aspects of production processes that do not relate to the machine reliability. This article considers the equations of the machine productivity that include only technical aspects of the machine and do not include aspects of management and maintenance at a prescriptive overhaul time of machine repair. Total management concepts consider service of the production process and do not have the right dependencies on machine productivity rate and its reliability. Total maintenance concepts consider the machine when it is out of work, that is, planned repair and service of machines stopped for overhaul processes, and do not consider random stops of machines. These concepts of management and maintenance do not take into consideration the reliability indices of a machine. However, consideration of a machine lifespan is included in a general index of machine efficiency.

This article considers the current machine productivity rate. Such an approach can simplify analytical dependency of the productivity rate and integrated index of the machine reliability. The main index of availability is the integrated index of reliability and it is the component of equations of the productivity rate for automated lines. The integrated index of machine reliability unites standard indices of reliability of a machine and other indices of technical characteristics that reflect the machine productivity rate.

The machine productivity has units of measurement such as the number of products produced per period of observation time. Generally, the number of products can have dimensions in discrete units, weight units, length units, area units, volume units, and so on, which depend on the type of production process. Then, the productivity rate of machines has

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dimensions products (parts)/time, m/time, $m^2$/time, $m^3$/time, kg/time, and so on.
Manufacturing processes have mainly discrete production and the productivity rate of a machine is represented by the following equation if the idle time due to managerial and organizational problems is not considered [1,5].

$$Q = \frac{z}{\theta} = \frac{z}{\theta_w + \theta_i} = \frac{1}{\frac{\theta_w}{z} + \frac{\theta_i}{z}} = \frac{1}{T + \sum_{i=1}^{n} t_{ei}} \qquad (3)$$

where $z$ is number of products machined per observation time.
The observation time $\theta = \theta_w + \theta_i$ is presented as the sum of the machine work time $\theta_w$ and idle time due to technical failures of a machine, $\theta_i$. If the nominator and denominator of Eq (3) are divided by the number of products $z$ then the ratio $\theta_w/z = T$ represents the cycle time for the machining of one part. The cycle time $T = t_{mo} + t_a$ represents the sum of machining time, $t_{mo}$ (min/part), of the total technological process and the auxiliary time $t_a$ (min/part), which includes time spent loading and reloading work-pieces to the machining area, clamping and relieving the part, fast forward motion of supports with cutters to work-pieces and back after machining, and so on.
The idle time is expressed by the equation $\theta_i = m_r * b$, where $b$ is the number of machine stops. The work time is expressed by the equation $\theta_w = m * b$, whose parameters are specified above.

The ratio of $\frac{\theta_i}{z} = \sum_{i=1}^{n} t_{ei}$ is total time losses referring to one product due to reliability reasons of $n$ machine units (the expression "time losses" is used for simplicity).

The total time losses due to reasons related to the reliability of machine units can also be presented by the sum of time losses of separate units. Generally, machines with complex design have common technical units and devices like a control system, an actuator with gearing, a transport mechanism, and so on that serve the whole machine. Also, these types of machines have units of similar designs like head power, stations, spindle units, and so on with more or less equal reliability levels. In such cases the time losses of similar units can be expressed by multiplication of the average time losses of one unit by the number of similar units in a machine with complex design. This thesis can be presented by the following expression:

$$\sum_{i=1}^{n} t_{ei} = \frac{\theta_c}{z} + \frac{q\theta_u}{z} \qquad (4)$$

where $\theta_c$ is the time losses due to common mechanisms and units, $\theta_u$ is the average time losses due to single similar mechanisms and units, $q$ is the number similar mechanisms and units, and other parameters are specified above.

Substituting the defined parameters into Eq. (3) and transformation gives the following equation of the productivity rate of a machine:

$$Q = \frac{1}{T} * \frac{1}{1 + \left(\sum_{i=1}^{n} t_{ei}\right)/T} = \frac{1}{t_{mo} + t_a} * \frac{1}{1 + \left(\sum_{i=1}^{n} t_{ei}\right)/(t_{mo} + t_a)} = Q_T A \qquad (5)$$

The expression $Q_T = 1/T = 1/(t_{mo} + t_a)$ is the cyclic productivity of a machine, that is, 1 product per $T$ time or part/min. Then, the availability of a machine after substituting all of the defined parameters and transformation is expressed by the following equation:

$$A = \frac{1}{1 + \left(\sum_{i=1}^{n} t_{ei}\right)/T} = \frac{1}{1 + \frac{\theta_i}{zT}} = \frac{1}{1 + \frac{\theta_i}{\theta_w}} = \frac{1}{1 + \frac{m_r b}{mb}} = \frac{1}{1 + \lambda m_r} \qquad (6)$$

where all parameters are as presented above.
Equation (6) is the same as Eq. (2) of the availability of a machine and includes the failure rate of a machine $\lambda$ and repair and maintenance time $m_r$ due to random failure of a machine but does not include prescribed planned overhaul repair time. In cases when the overhaul repair time, maintenance time, and idle time due to management problems are included, it is considered that the efficiency of a machine not only reflects technical problems, but also includes management and service problems of a machine, which is beyond the scope of consideration of this paper.

Availability is considered as the integrated index of reliability of a machine and is a very important index of quality. Substituting Eq. (6) of availability into Eq. (5) gives the following equation of the productivity rate of a machine:

$$Q_t = \frac{1}{t_{mo} + t_a} * \frac{1}{1 + m_r \lambda} \qquad (7)$$

Equation (7) of the machine productivity includes parameters of the machining time $t_{mo}$, auxiliary time $t_a$, and availability of a machine. The defined parameters of the productivity rate of a machine enable new analytical equations of the productivity rate and reliability of industrial machines with complex designs like automated lines with different structures to be obtained.

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## AVAILABILITY IS A COMPONENT OF THE PRODUCTIVITY RATE OF THE ROTOR-TYPE AUTOMATED LINE

In industrial areas there are many types of multi-station technological machines with complex design, whose productivity rate is calculated by different equations. For example, the rotor-type automated production line (Fig. 1) is a complex design of technological machine with its own technical parameters. The rotor-type automated production line belongs to machines of serial-parallel action. The single rotor-type automatic machine is the multi-station's machine of parallel action. The main difference between the rotor-type automatic machine and other designs of the multi-station's machine of parallel action is that the machining process of the part is shifted at the time at each station. Another difference is that the rotor-type automatic machine has one mechanism for loading and reloading the parts for all stations. The number of such mechanisms of a multi-station's automatic machine of parallel action of linear composition is equal to the number of parallel stations. The scheme of a multi-station's automatic machine of parallel action is presented in Fig. 2. The scheme of a multi-station's automatic machine of serial-parallel action is presented in Fig. 3.

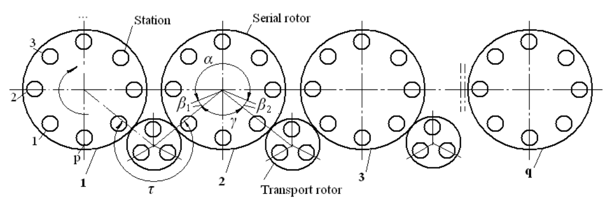


***Figure 1. The work structure arrangement of the rotor-type automated line of parallel-serial action with p parallel stations and q serial ones***

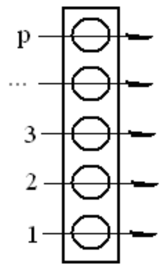


***Figure 2. Scheme of a multi-station machine of parallel action with p stations***

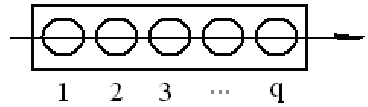


***Figure 3. Scheme of a multi-station machine of serial action with q stations***

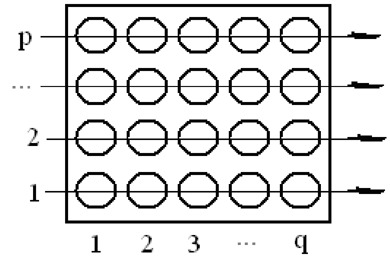


***Figure 4. Scheme of a multi-station automated line of serial-parallel action with q serial and p parallel stations and linear arrangement***

Industrial practice shows that the design of a multi-station automated line of serial-parallel action with $q$ serial and $p$ parallel stations with linear arrangement is quite a complex task due to many restrictions. Practically, manufacturers produce such automated lines with two parallel flows embedded in one system and very rarely three parallel flows for the short automated lines.

The design of automated lines with serial-parallel action is executed by two types of automated production line structures. The first type of automated production line of serial-parallel actions has a linear arrangement and is applied for processes having long cycle times like machining of housing parts, shafts of complex design, and so on. The second type has a rotor-type arrangement (Fig. 1) with $p$ parallel and $q$ serial stations, which are more compact and more convenient from the point of view of design, maintenance, and service. Such automatic machines are called rotary machines and have found wide application in various branches of industry like pressing, coining, liquid filling of bottles, and so on. The analytical dependencies of productivity rate of these two types of machines are different.

A rotor-type automated line has the following work process (Fig. 1). The working rotor has a continuous transport motion and contains working stations with tools for fulfilling the assigned operations. During the rotation of the working rotor, work-pieces are processed. In zone $\beta_1$, a work-piece is loaded and a tool approaches a work-piece rapidly. In zone $\alpha$ a technological process (stamping, drawing, assembling, etc.) is performed. In zone $\beta_2$, a tool is

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withdrawn and a processed part removed. In zone $\gamma$, a tool is inspected and cleaned. Zone $\alpha$ carries out the machining process ($t_{mo}$), whereas zones $\beta_1$ and $\beta_2$ carry out auxiliary motions ($t_a$) [8,9]. Any failure of serial or parallel stations leads to stopping of a whole rotary automated line, due to the mechanical hard joining of all mechanisms. A rotor-type automated production line can be considered as a system of collection of serial and parallel stations arranged according to a certain structure that depends on a technological process of machining parts. These subsystems are serial and parallel stations and other units.

The theory of reliability refers to reliability modeling, analyzing components and their relationships that relate to the system state (working or failed), reliability evaluation, and so on. System reliability analysis tools are the Reliability Block Diagram (RBD), Fault Tree Analysis (FTA), and Failure Mode and Effect Analysis (FMEA) [1–5].

Practically, in the area of manufacturing processes and industrial machines with complex design, it is assumed that the average reliability of each machine or station in the system is the same. In the case of the rotor-type automated line, one principle is accepted for serial and parallel stations (machines): the system fails if at least one of the stations fails, that is, a serial or a parallel. The failure of common mechanisms of machines with complex design is considered separately. The result of this principle is that the increase in time losses according to Eq. (4) is expressed as follows:

$$qp_s\sum_{i=1}^{n} t_{ei} + t_c = \frac{qp_s\theta_s}{z} + \frac{\theta_c}{z} \qquad (8)$$

where $\theta_s$ is the idle time of one station, $\theta_c$ is the idle time of common mechanisms, $p_s$ is the number of parallel stations, $q$ is the number of serial stations, and other parameters are as specified above.

A corrected analytical expression of the productivity rate of the rotor-type automatic line of serial-parallel action has been developed and presented in the publication [9]. The equation of the productivity rate of the rotor-type automatic line is expressed as follows:

$$Q_{pq} = \frac{p}{\left(\frac{t_{mo}}{q} + t_a\right)\left(2 + \frac{p_\gamma + p_t - 1}{p_s - p_\gamma}\right) + (t_s + t_t)p_s q + t_c} \qquad (9)$$

where $p$ is the number of products (each station carries one product, that is, the number of products is equal to the number of stations, $p = p_s$), $q$ is the number of serial stations, $t_{mo}$ is the machining time of the total technological process, $t_a$ is the auxiliary time, $t_c$ is the time losses due to reliability of common mechanisms (actuator, control unit, etc.), $t_s$ is the time losses due to reliability of the station's mechanisms, $t_t$ is the time losses due to reliability of the transport mechanism, $p_t$ is the number of stations located on the transport angle $\tau$ of the transport rotor, $p_\gamma$ is the number of stations located on the idle angle $\gamma$ of the rotor machine (Fig. 1), and other parameters are as presented above.

Equation (9) of the productivity rate of the rotor-type automated line has components that represent structure, that is, the number of serial ($q$) and parallel stations ($p_s$ ). The number of parallel stations ($p_\gamma$) does not involve the machining process due to design properties of the rotor machine, the number of parallel stations ($p_t$) involved in the process of transporting parts. Equation (9) includes parameters of the technological process ($t_{mo}$), design ($t_a$), and components of time losses due to technical reasons concerning the automated line that reflect its reliability and structure ($t_c, t_s$).
The expression given in Eq. (9)

$$\left(\frac{t_{mo}}{q} + t_a\right)\left(2 + \frac{p_\gamma + p_t - 1}{p - p_\gamma}\right) = T\left(2 + \frac{p_\gamma + p_t - 1}{p - p_\gamma}\right) = Td$$

Is the processing time of $p$ products, where $d = 2 + \frac{p_\gamma + p_t - 1}{p - p_\gamma}$ is the cycle time displacement factor.
Analysis shows that Eq. (9) consists of the cyclic productivity, displacement factor, and availability of a rotor-type automated line. Availability is expressed after transformation of Eq. (9) and substitution of the cycle time of the automated line by the following equation:

$$Q_{pq} = \frac{p}{Td}\left(\frac{1}{1 + \frac{(t_s + t_t)pq + t_c}{Td}}\right) = Q_{Td}A, \qquad (10)$$

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where the first component of Eq. (10) is the displaced cyclic productivity of the rotor-type automated line:

$$Q_{Td} = \frac{p}{T\left(2 + \dfrac{p_\gamma + p_t - 1}{p - p_\gamma}\right)}, \tag{11}$$

The second component of Eq. (9) is the availability of the rotor-type automated line:

$$A = \frac{1}{1 + \left[\{(t_s + t_t)pq + t_c\} \Big/ T\left(2 + \dfrac{p_\gamma + p_t - 1}{p - p_\gamma}\right)\right]} = \frac{1}{1 + \left[\{(t_s + t_t)pq + t_c\}/Td\right]} \tag{12}$$

The availability of an automated line $A$ includes the time losses due to technical reasons, ($t_c$, $t_s$, $t_t$), which reflect the reliability parameter of the mechanisms and station, and its structural parameters ($q$, $p$). The availability of the rotor line is an integrated index of reliability of the automated line, and gives a correct result compared to other similar indices of reliability that are presented in common forms [3–5]. However, the displacement of the cycle time of the machining process at each station does not reflect the availability level of the whole automated system. This statement will be proved below.
The time productivity losses due to technical reasons ($t_c$, $t_s$, $t_t$) can be expressed by the standard indices of the reliability of a machine. The time losses of the rotor-type automated line due to technical reasons are calculated by the following equation:

$$(t_s + t_c)pq + t_c = pq\left(\frac{\theta_s}{z} + \frac{\theta_t}{z}\right) + \frac{\theta_c}{z}, \tag{13}$$

where $\theta_c$ is the idle time of the common mechanisms of a rotor machine, $\theta_s$ is the idle time of a working rotor machine with $p$ stations, $\theta_t$ is the idle time of a transport rotor, and $z = \theta_w/(Td)$ is the number of machined parts produced per period of observation time of work of a rotor-type automated line.

These idle times of the mechanisms and machines of an automated line due to technical reasons are also expressed by indices of reliability, $\theta_i = m_r b$, where $m_r$ is the mean time to repair, and $b$ is the number of stops. The machine's work time is expressed by the equation $\theta_w = m_w b = b/\lambda$, and $\lambda$ is a machine failure rate. Transformation of the expression of idle times can be done similarly to that shown above for a single machine.

In industry, the index of mean time to repair $m_r$ random failures of machine units is accepted to have an average magnitude of 2–3 minutes. However, the index of machine failure rate is different for different machine units. Hence, the equation of availability of the rotor-type automated line should include $\lambda_c$, $\lambda_s$, and $\lambda_t$, that is, the failure rates for common mechanisms, rotor stations, and transport rotor respectively.

After substitution of the reliability indices expressed above and transformation, the availability of the rotor-type automated line will be expressed by the following equation:

$$A = \frac{1}{1 + \left[\left\{pq\left(\dfrac{\theta_s}{\theta_w/(Td)} + \dfrac{\theta_t}{\theta_w/(Td)}\right) + \dfrac{\theta_c}{\theta_w/(Td)}\right\} \Big/ Td\right]} =$$
$$\frac{1}{1 + \left[\left\{pq\left(\dfrac{m_r b_s \lambda_s Td}{b_s} + \dfrac{m_r b_t \lambda_t Td}{b_t}\right) + \dfrac{m_r b_c \lambda_c Td}{b_c}\right\} \Big/ Td\right]} = \frac{1}{1 + m_r\left[pq(\lambda_s + \lambda_t) + \lambda_c\right]} \tag{14}$$

where all parameters are as specified above.
The availability of the rotor-type automated line (Eq. (14)) contains standard indices of reliability of mechanisms ($m_r$, $\lambda_i$), and parameters of structure and design of the rotor-type automated line ($p$, $q$). This means that the availability as the integrated index of reliability of the complex design machine depends on the standard indices of reliability of a machine and on structural parameter indices.

After substituting Eq. (14) into Eq. (10), the productivity rate of the rotor-type automated line will have an equation that contains all the technical parameters and an integrated index of the reliability of the line. This integrated index includes the mean time to repair ($m_r$), machine failure rates ($\lambda_i$), and structure of the rotor-type automated line ($p$, $q$).

$$Q_{pq} = \frac{p}{\left(\dfrac{t_{mo}}{q} + t_a\right)\left(2 + \dfrac{p_\gamma + p_t - 1}{p - p_\gamma}\right)} * \frac{1}{1 + m_r\left[pq(\lambda_s + \lambda_t) + \lambda_c\right]}, \tag{15}$$

where all parameters are as specified above.
Equation (9) of the productivity of the rotor-type automated line and Eq. (14) of its availability enable important engineering problems to be solved. It is possible to calculate the necessary level of reliability of the rotor-type automated line according to the requested productivity rate or vice versa. If the magnitudes of reliability indices of the components

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of the automated line are known, it is easy to calculate its productivity rate.

## A COMPONENT OF THE PRODUCTIVITY RATE

Equation (15) of the productivity rate of the rotor-type automated line can be transformed according to the specificity of design and structure of the automated line with serial-parallel action and linear arrangement. The schematic diagram of such a line is presented in Fig. 4. Obviously, the specificity of design for the automated line with serial and parallel actions and linear arrangement can be presented by the following properties: all stations begin to work at one time and after finishing operations the parts are transported by the linear design of the transport mechanism to the following stations.

Hence, from Eq. (15) of the productivity rate of the rotor-type automated line, the component of the cycle time displacement factor *d* should be omitted, and then the productivity rate with availability of automated lines of serial-parallel action and linear arrangement will have the following equation:

$$Q_{pq} = \frac{p}{\left(\frac{t_{mo}}{q} + t_a\right)} * \frac{1}{1 + m_r\left[pq(\lambda_s + \lambda_t) + \lambda_c\right]} \tag{16}$$

For automated lines with serial action and linear arrangement (Fig. 3), when the number of parallel flows is one ($p$ = 1), the equation of the productivity rate with availability will be as follows:

$$Q_{pq} = \frac{1}{\left(\frac{t_{mo}}{q} + t_a\right)} * \frac{1}{1 + m_r\left[q(\lambda_s + \lambda_t) + \lambda_c\right]} \tag{17}$$

For automated lines with parallel action and linear arrangement, when the number of parallel stations is $p$ and the number of serial stations $q$ = 1 (Fig. 2), the equation of the productivity rate with availability will be as follows:

$$Q_{pq} = \frac{p}{(t_{mo} + t_a)} * \frac{1}{1 + m_r\left[p(\lambda_s + \lambda_t) + \lambda_c\right]} \tag{18}$$

Equations (16)–(18) are derived from Eq. (15) by simplifications due to constructional and structural properties of these types of automated lines as mentioned above.

## THE INDUSTRIAL CASE STUDY

In some manufacturing areas, there are normative data of availability of machines located within 80 – 85%, that is, $A = 0.8 - 0.85$, and mean time repair $m_r$ = 2–3 min. These normative data also enable engineering problems that concern the level of the availability, single indices of reliability of a machine, structural and technical parameters, and the productivity rate of a machine to be solved.

### *1. The rotor-type automated production line*

Assume that the rotor type automated production line can be designed with variants. It can have the following data: $q$ = 4, 5, 6 is the number of machining stations of the rotor line, $p$ = 10, 12, 14 is the number of parallel stations of the machining rotor, $p_\gamma$ = 4 is the number of idle stations of the machining rotor, $p_t$ = 2 is the number of transport stations in the transport rotor, $t_{mo}$ = 1 min/part is the machining time, $t_a$ = 0.1 min/part is the auxiliary time, $m_r$ = 3 min is the average repair time of the rotor-type automated line, $\lambda_s = \lambda*10^{-4}$ is the failure rate of a station of the automated line, $\lambda_c = \lambda_t = \lambda*10^{-8}$ is the failure rate of common mechanisms, and the transport rotor is very small, and can be neglected.

After substituting these data into Eq. (8) and Eq. (9) and calculating, the results of availability of the rotor-type automated line and its productivity versus the failure rate are presented in Fig. 5. The diagram shows that increasing the failure rate of the automated line decreases the magnitude of availability of the rotor-type automated line. Increasing the number of parallel and serial stations of the automated line reflects the magnitude of availability of the automated line: the more stations, the less availability.

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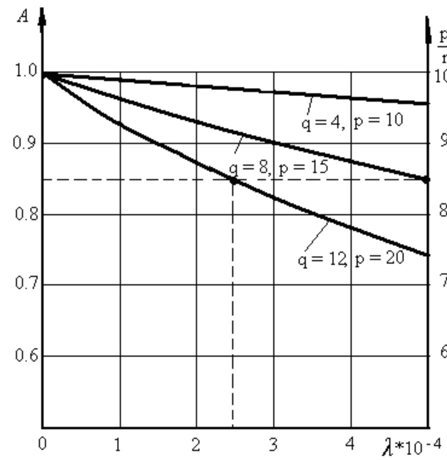


***Figure 5. Productivity rate and availability of the rotor-type automated line with q and p parallel stations versus the increase in the failure rate λ of the automated line***

If the availability accepted is $A$ = 0.85 then:

- an automated line with $q$ = 12 serial and $p$ = 20 parallel stations should have a failure rate of $\lambda \leq 2.4.0*10^{-4}$ failures/min,
- an automated line with $q$ = 8 serial and $p$ = 15 parallel stations should have a failure rate of $\lambda \leq 5.0*10^{-3}$ failures /min.

These two structural variants of the rotor-type automated line give the technical productivity rate $Q_t$ = 8.5 parts/min.

The automated line with $q$ = 4 serial and $p$ = 10 parallel stations has quite a low failure rate and high reliability, and gives a higher productivity rate.

Evaluation of which structure of the line is preferable should be performed according to the criterion of economical efficiency. Increasing the reliability and changing the structure of the automated line leads to changes in the cost.

Generally, increases in the number of parallel stations and decreases in the number of serial stations of the rotor-type automated line are not reflected proportionally in the productivity rate of the rotor type automated line [6,10]. Therefore, the changes in the number of parallel or serial stations of the automated line should be calculated according to the necessary level of the productivity rate and then the magnitude of availability should be chosen as an integrated index of reliability of the automated line. Finally, manufacturers of an automated line should evaluate the technical characteristics according to the criterion of economical efficiency.

***2. The serial section-based automated line with buffers of limited capacity.***

Assume that the section-based automated production line with embedded buffers has the following data: $q$ is the number of machining stations, $n$ is the number of sections, $t_m$ = 1 min/part is the machining time, $t_a$ = 0.3 min/part is the auxiliary time, $\Delta$ = 0.1 is the average coefficient of the inter-sectional imposition of productivity losses, $m_r$ = 3 min is the average repair time of a machine or station, and $\lambda_b$ and $\lambda_c$ are the failure rates of a buffer and common mechanisms, which are small and can be neglected. After substituting these data into Eqs. (19) and (22), the results of the availability and the productivity rate of the automated line as a function of the failure rate are presented in Fig. 6.

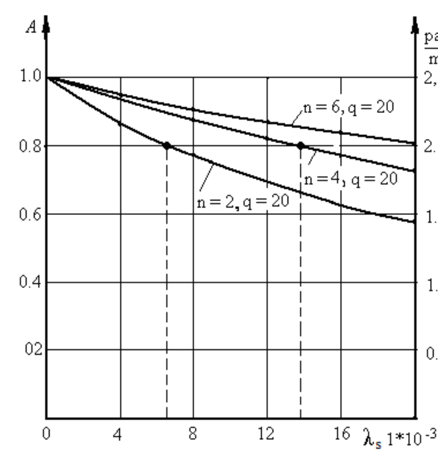


***Fig. 6. Availability and productivity rate of the section-based automated line with q stations segmented into n sections versus the increase in the line failure rate λ***

The diagram shows that increasing the line failure rate decreases the magnitude of availability and the productivity rate of the automated line. Increasing the number of sections and number of stations in the automated line increases the magnitude of availability and also increases the productivity rate of the automated line. If the accepted availability is $A$ = 0.8 then:

- an automated line with n = 2 sections and q = 20 stations should have a failure rate of $\lambda \leq 6.5*10^{-3}$ failures/min,
- an automated line with n = 4 sections and q = 20 stations should have a failure rate of $\lambda \leq 13.7*10^{-3}$ failures/min,
- an automated line with $n$ = 6 sections and $q$ = 20 stations should have a failure rate of $\lambda \leq 20*10^{-3}$ failures/min.

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Therefore, increasing the number of sections in the automated line can compensate for its low level of reliability. The increase in the number of sections in the automated line does not reflect proportionally the increase in availability of the automated line.

## RESULTS AND DISCUSSION

The results and discussion may be combined into a common section or obtainable separately. They may also be broken into subsets with short, revealing captions.

Derived equations of availability of typical automated lines with complex designs show that availability depends on:

standard indices of reliability of mechanisms;

parameters of structure and design of the automated line, that is, the number of serial and parallel stations and the number of sections of the automated lines; and technical parameters like the capacity of the buffer.

Equations enable calculation of the magnitude of availability of the automated line as a function of the reliability indices and the technical and technological parameters. The derived equations were tested on section-based serial and rotor-type automated production lines respectively. The results of calculations enable the necessary tolerances of availability and other technical and technological parameters of the section-based serial and rotor-type automated production lines to be defined as a function of the productivity rates of automated lines.

## CONCLUSION

The productivity of any complex industrial machine depends on the technological process, reliability of units, and structure of the machine. Analytical study of the influence of reliability, technological, and technical parameters on the machine output shows that there is a strong mathematical dependency of the productivity rate and availability of the industrial machines.

The contribution of this paper is the development of analytical equations of the availability of the typical designs of industrial automated lines. This main index of the reliability of industrial machines with complex design depends not only on standard indices of reliability of mechanisms but also on parameters of structural design and technical data of complex industrial machines.

The equations of availability for the typical designs of automated production lines give results based on the indices of reliability of mechanisms and machines and on the structure and technical parameters of the units of automated lines.

The equations of availability and productivity rate will be useful in modelling the output of automated lines, defining the structure, and determining the number of parallel and serial stations and also the capacity of the buffers according to the necessary level of reliability of complex design industrial machines. Engineers and designers of automated lines can use the derived analytical results in the project stage of the automated line design.

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