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Simulation model of robotic manufacturing line

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***Abstract*—The problem of production flow in the manufacturing line is analyzed. The machines can be operated by workers or by robots. Since breakdowns and human factors affect the destabilization of the production processes, robots are preferred to apply. The problem is how to determine the real difference in work efficiency between human and robot. Analysis of the production efficiency and reliability of the press shop lines operated by human operators or industrial robots are presented. This is a problem from the field of Operation Research area and Discrete Events Simulation (DES) method have been used. Two models have been developed including manufacturing line before and after robotization and taking into account stochastic parameters of availability and reliability of the machines, operators and robots. We apply OEE (Overall Equipment Effectiveness) indicator to present how the availability and reliability parameters influence over performance of the workstation, in particular in the short time and long time period. Also the stability of simulation model was analyzed.**

I. Introduction

THE industrial revolution caused the replacement of human labor by machinery. However, workers were still needed to handle and control the machines. Now we can see increasing use of automation and robotization, which replace human labor. Nowadays increased use of industrial robots can be observed especially for repetitive and high precision tasks (e.g. welding) or activities of monotonous and demanding physical exertion. Industrial robots have mobility similar to human arm, and can perform various complex actions like a human. In addition, they do not get tired and bored. It is estimated that thanks robotization, many companies obtained the reduction of the production cost by 50%, the increase of productivity by 30% and the increase of utilization by more than 85% [1].

However, the introduction of robotization requires incurring high costs, therefore robotization will be profitable only in certain circumstances, including, a high level of production, work with repetitive and precision tasks with ensuring the safety and health at work. Such conditions occur in the automotive industry and there the most robots are used.

The problem is how to determine a real difference in work efficiency between human and robot. The aim of the study is to develop a methodology, which allows to clearly define the throughput growth associated with the replacement of human labor by industrial robots. In order to assess the effectiveness of the robot application, we compare production uptime of humans and robots and calculate work efficiency with the use of the OEE indicator (Overall Equipment Effectiveness) and we use Discrete Event Simulation for verification.

II. Work efficiency and OEE Structure

Work efficiency and the use of the means of production can be expressed by using the OEE metric that depend on three factors: availability, performance and quality [2].

$$OEE=(Availability)x(Performance)x(Quality) \quad (1)$$

Availability is the ratio of the time spent on the realization of a task to the scheduled time. Availability is reduced by disruptions at work and machine failures.

$$Availability=\frac{avaliable\ time-failure\ time}{scheduled\ time} \quad (2)$$

Performance is the ratio of the time to complete a task under ideal conditions compared to the realization in real conditions or the ratio of the products obtained in reality to the number of possible products to obtain under ideal conditions. Performance is reduced (loss of working speed) by the occurrence of any disturbances e.g. human errors.

$$Performance=\frac{ideal\ cycle\ time}{real\ cycle\ time} \quad (3)$$

Quality is expressed by the ratio of the number of good products and the total number of products.

$$Quality=\frac{good\ products}{overall\ products} \quad (4)$$

The number of good quality products is a random variable, which can be described by a normal distribution with standard deviation sigma. Quality levels are determined for ranges of the standard deviation sigma. In traditional production systems, level of 3 sigma is considered to be sufficient. However, in the modern automated and robotic systems the level of 5-6 sigma is possible to achieve [3].

A. Availability and failures

The term of availability contains planned work time and unplanned events e.g. the disturbances at work and random machine failures. Any unplanned event causes that machines are unavailable and work efficiency decreases. The reliability of objects such as machines or robots is defined as the probability that they will work correctly for a given time under defined conditions of work. The most popular method for estimating reliability parameters uses theory of probability to forecast a value of failure-free time and repair time parameters, under the condition that a trend based on historical value of the parameter is possible to notice. The examples of using normal, exponential, triangular distributions to describe both failure and repair times are described in [4]. In the article [5], it is assumed that parameters of distributions describing failure-free times, in general, change with time. Basing on information about the number of failures and failure-free times in a number of periods of the same duration in the past, some methods of estimation unknown parameters for scheduling purpose can be proposed [6].

In practice, for description of reliability, in most cases the parameter MTTF (mean time to failure) is used, which is the expected value of exponentially distributed random variable with failure rate λ [7].

$$MTTF = \int_0^\infty t\, f(t)\, dt = \int_0^\infty t\, \lambda\, e^{-\lambda x}\, dx = \frac{1}{\lambda} \tag{5}$$

In the case of repairable objects the parameters MTBF (mean time between failures), and the MTTR (mean time to repair) are used.

$$MTBF = MTTF + MTTR \tag{6}$$

For complex systems, consisting of n serially linked objects, the resultant failure rate λ_s of the system is the sum of the failure rates of each element λ_i:

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{7}$$

or the system $MTBF_s$ is the sum of inverse $MTBF_i$:

$$\frac{1}{MTBF_s} = \sum_{i=1}^{n} \frac{1}{MTBF_i} \tag{8}$$

For the example of robotic line, presented in figure 1, we can use formula 8 with different failure parameters for machines $MTBF_{mi}$ and for robots $MTBF_{ri}$:

$$\frac{1}{MTBF_s} = \sum_{i=1}^{n} \frac{1}{MTBF_{mi}} + \sum_{i=1}^{n+1} \frac{1}{MTBF_{ri}} \tag{9}$$

Machinery failures affect the availability of means of production and may cause severe disturbances in production processes. Average availability can be calculated with formula 10.

$$Availability = \frac{MTBF}{MTBF + MTTR} \tag{10}$$

Therefore, the longer the production line is, the higher the failure rate of the whole system. In industrial environment, the machine failures are mostly random and are difficult to predict; therefore, we have used computer simulation for further research [8].

III. Robotic Factor in Manufacturing

Manufacturing lines consist of different numbers of specialized machines and human operators or robots for materials handling. Usually, operator is required for loading and unloading the machine and for transferring the product from one machine to next production stage. Robots can make that work faster and more regular then human operators, but how fast a robot can work?

There are some methods for robot motion planning described in [9] and [10]. These methods are based on the MTM (Method Time Measurement) or on the traditional time study concept and can be used for comparing the relative abilities of robots and humans. Dedicated computer software for robot movement planning can be also used. The outcome of each technique is a set of time values that can be used to compare human and robot productivity.

In industry, there are many different types of machine tools, and presses are the most robotized. The schema of typical robotic press line is presented in the Figure 1.

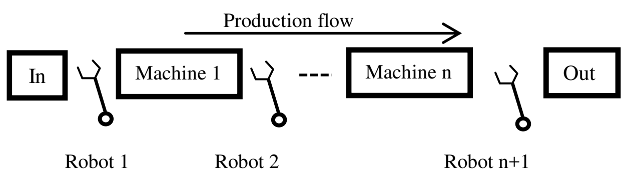

Fig. 1 The schema of robotic machine tending line

Robotized and automated lines are working very well but some problems with failures can occur. A failure of any elements of the line causes production stopping of the whole production line. Therefore, reliability of the components plays a key role for the productivity and utilization of manufacturing system. Consequently, in practice, the production lines consist mostly between 4 and 6 machines.

Modern industrial robots are characterized by a large precision of operation, high speed of motion and high reliability of work. These can be equipped with a various tools and used to different works that are traditionally performed by human workers. It is important that the robots can work in conditions harmful to human health.

Some new-generation robots are equipped with various intelligent sensors, e.g. vision and pattern recognition systems, and they are able to adapt to changing conditions of external surroundings. New robots generation have also greater speed than older ones and can have important effect on robotic system performance.

Theoretically, robots can work 24 hours per day without any breaks, but human supervision of the production process and precise planning and scheduling of robot work are necessary for better performance [11]. Realized from time to time changes of tools and reprogramming require participation of an operator. Moreover, robot requires periodic maintenance service and inspection before each automatic run.

A. Robot reliability

For the first type of robots (Unimate) uptime was equal to MTBF=500 hours [10]. In article [12] the results of research on robots reliability at Toyota are presented. The reliability of first robot generation represents the typical bathtub curve. The next generation of robots was characterized by MTBF about to 8000 hours. Nowadays, robot manufacturers declare average MTBF=50000÷60000 hours or 20÷100 million cycles of work [13]. However, the robot's equipment is often custom made and therefore may turn out to be unreliable.

Some interesting conclusions from survey about industrial robots conducted in Canada [14] are as follows:

- Over 50 per cent of the companies keep records of the robot reliability and safety data,
- In robotic systems, major sources of failure are software failure, human error and circuit board troubles from the users' point of view,
- The most common range of the experienced MTBF is 500-1000 hours,
- Most of the companies need about 1-4 hours for the MTTR of their robots,

In the book [1] the approximate efficiency of robotic application versus manual application was compared. The efficiency of manual machine tending is about 40-60% and for robotic machine tending is about 90% (not including time for changeover setup equipment). However, detailed values are dependent on the specifics of the real workstation.

IV. EXAMPLE–PRESS LINE WITH WORKERS AND ROBOTS

In order to analyze the presented problem the mechanical press line from enterprise X, has been taken into account. Presses are often used in various production processes e.g. pressing, sheet metal forming etc. We have used Enterprise Dynamics software, which allows computer-modeling and simulation of discrete production processes with the use of human resources as well as robots.

In computer software used for production processes simulation the human factor is not sufficiently modelled. People are treated as quasi-technical elements of production system and they should operate in the same way as a machine. In practice, the human behaviour is unpredictable, thus it might help to explain why simulation models do not respond to the reality as it would be expected [15]. In the case of a manually-operated systems, a number of human factors (human errors) can lead to destabilization of the manufacturing process. Breaks for rest and higher requirements for Health and Safety at Work require a different way of working [16].

Computer models of lines operated by robots as well as by humans have been developed, taking into account the planned breaks at work and failure rates (Fig. 2, 4 and 5). The models contain the input (Source), storage buffers (Queue), machines, robots, human resources (Operators), output element for good quality products (Good parts) and one for poor quality products (Bad parts) and control elements (Availability Control, Schedule, MTBF, MTTR).

Unlimited supply of input materials and unlimited capacity for output products were assumed. Model contains some constrains, which are defined in objects parameters for example maximal buffer capacity.

The first model of robotic line without failures (Fig. 2), represents high production efficiency and achieve OEE above 90%, which is heavily dependent on the speed of robots movement.

Modern robots are characterized by increased speed and thanks to this, it is possible to obtain greater productivity. To examine the scale of this phenomenon several simulation with varying speed of the main robot axis, changing from 60 °/s to 210 °/s were conducted.

The relation between robot speed and robotic line productivity is presented in Figure 3. Initially, increased robot speed have allowed for a significant increase in production throughput. However, further increase of the robot speed does not increase the efficiency significantly.

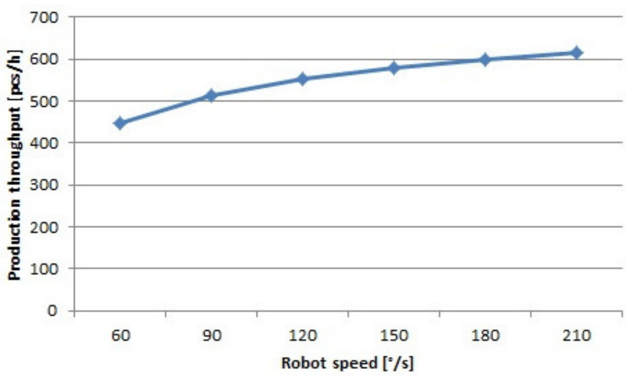

Fig. 3 Relation between productivity of robotic line and robot speed

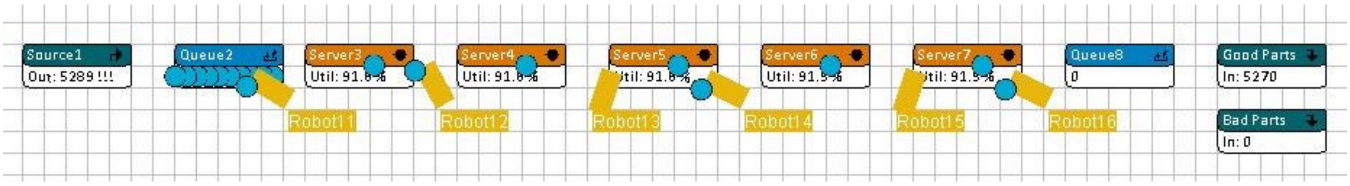

Fig. 2 Model of robotic line without failures after 8 hours of simulation

In practice reliability of machines and human errors are important issues. We take into account production parameters from enterprise "X". We assume that other employee can replace sick and absent worker, but it is impossible to replace broken machines and robots and they require repairing. In the case of failure occurrence the suspension of production on all machines in the line occurs. It has a huge impact on the performance of work, therefore we are taking into account failure parameters of machines and robots. The model include a number of work parameters: machine cycle time Tm=5 seconds; time of the line retooling 15 minutes (one time per shift) and reliability parameters for machines, MTBFm=500 hours and MTTRm=4 hours and robots, MTBFr=1000 hours and MTTRr=4 hours. The efficiency of the line and the speed of the robot 180 °/s equals to throughput rate about Pr=9.67 PCs/min, which is consistent with the data presented in [17]. Machine utilization equals about 80%.

In order to compare results we have also tested a model of manually-operated press line before robotization to determine differences in productivity. Manually operated line model is presented in Figure 4. The model consists of five machines, five operators and six buffer storages (Queue) in order to ensure continuity with the irregular performance of individual operators.

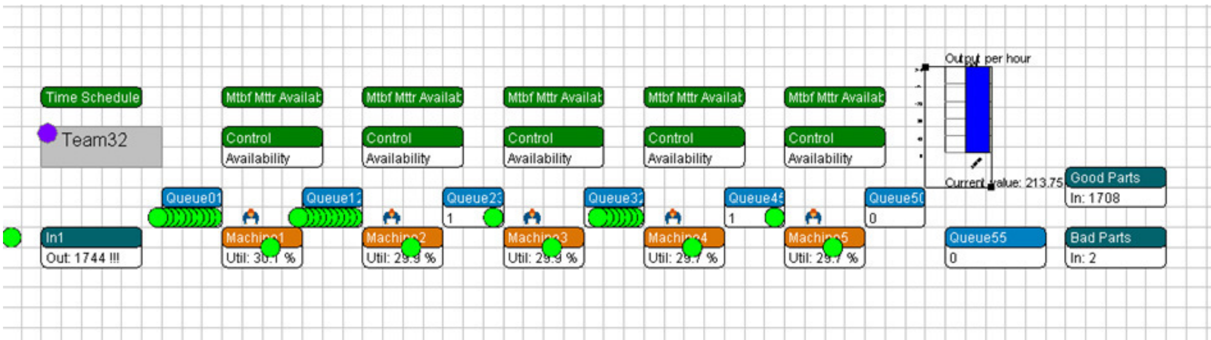

Fig. 4 Model of manually-operated line after 8 hours of simulation

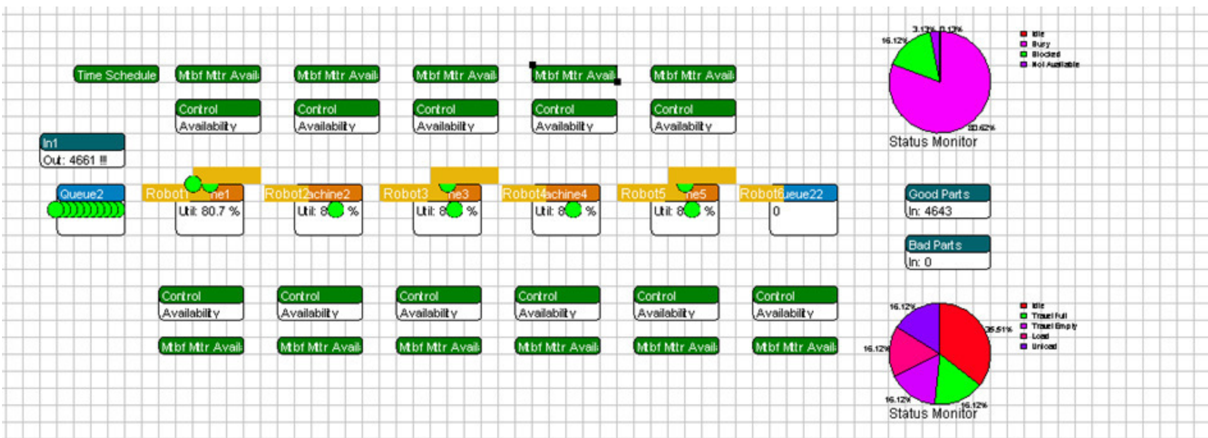

Fig. 5 Model of robotic line with failures after 8 hours of simulation

Parameters of operator were determined after time study and described by the normal distribution with average value of service time of 10 seconds and standard deviation of 2 seconds, which allows for implementation of nonuniformity in the work of the operators.

Assuming human unreliability on the basis of HEART (Human Error Assessment and Reduction Technique) for "routine and highly practiced rapid tasks involving relatively low level of skill", the nominal value of human error equals to 0.01 [18]. Therefore human errors rate can be described by parameters: MTBFh=8 hours and MTTRh=5 minutes. Taking into account the machine cycle parameters, Tm=5 seconds, the manually operated line should theoretically achieve production rate about P_h=4 PCs/min, but really the line achieved only about P_h=3.56 PCs/min. Utilization of machines equals around 30%.

The model of robotic line (Fig. 5) represents high production efficiency, which is heavily dependent on the speed of robots movement.

In addition, the stability of the production system and the impact of failure parameters on productivity and performance were analyzed in the similar manner as in the examples presented in [19]. A number of simulation experiments with different times of simulation runs were performed. Due to the random nature of a single failure process, a single simulation does not give complete picture of the situation. Therefore the experiment contains different number of simulations runs and simulation time from 8 hours to 6000 hours of work time. The trend lines of average production value for the manually operated line and for the robotic tended line are presented in Figures 6 and 7 respectively.

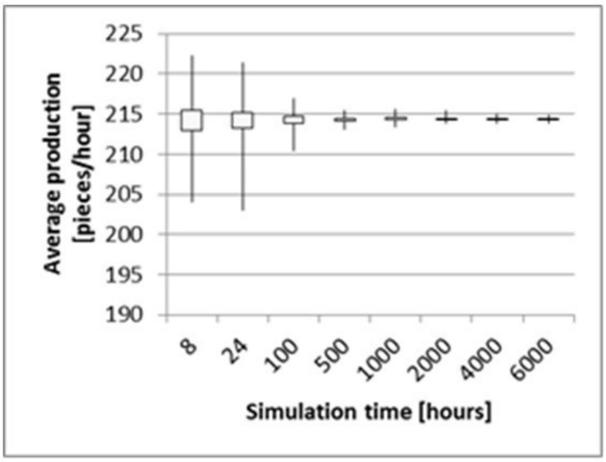

Fig. 6 The trend of average production value [pieces/hour] for manually-operated line (50 samples, confidence level 95%)

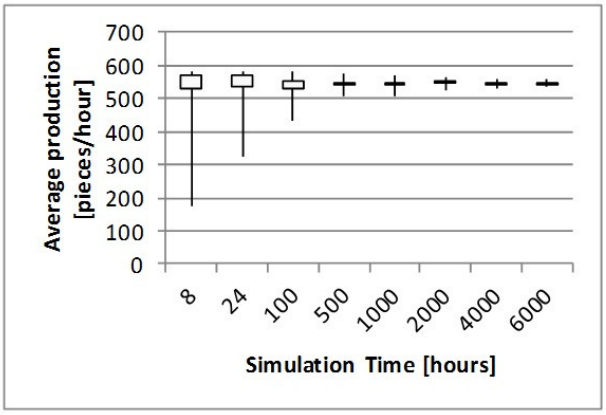

Fig. 7 The trend of average production [pieces/hour] value for robotic line (50 samples, confidence level 95%)

In the box and whisker plot, the average value of production is in the "box" range with confidence level of 95%. The "whiskers" show minimum and maximum range of production value.

The trends of average production value are more stable for longer simulation time. The model of robotic tended line show little difference with model of manually operated line. There are some outliers (the most extreme observations) represented by the minimum values of production that are connected with random failures and asymmetrical distribution with the left skewness can be observed (Fig. 8).

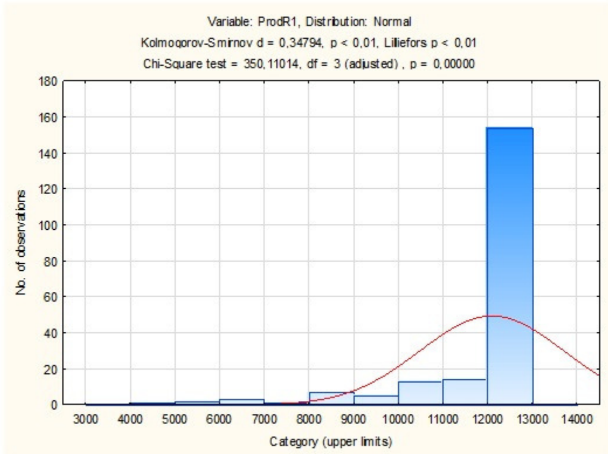

Fig.8 Histogram of production variable for robotic line after 24 hours of simulation

In other hands almost symmetrical normal distribution can be observed in the case of manually operated lines (Fig. 9).

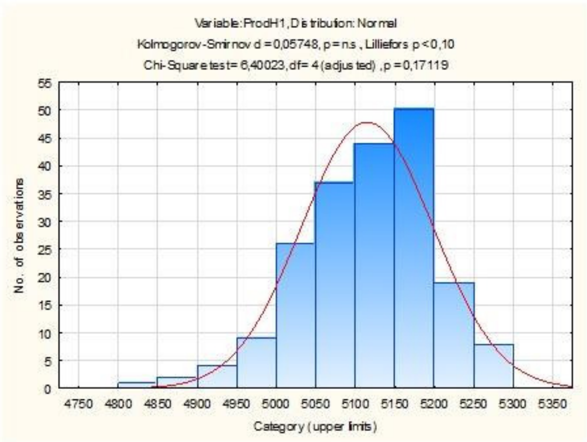

Fig. 9 Histogram of production variable for manual line after 24 hours of simulation

A number of fifty computer simulations for the simulation time from the range of 8 hour to 250 working days (one, two and three shifts and 250 working days per year) were run in order to observe the influence of long-term failures. For longer simulation time both models show decreased deviation and greater stability. Detailed results of the experiments are presented in the next section.

V. Simulation results

The production value P obtained from one simulation is a random variable that consists of several parameters. The random nature of the failures causes a significant dispersion of obtained values and relatively large standard deviation for confidence level α=0.95. The average production value P_{avg} of simulation experiments are summarized in table 1. Each experiment consists of fifty samples (simulation runs). The value *MaxLimit* determines the maximum possible production volume in a given period of time at the ideal working conditions for machine cycle time (Tm=5 seconds). Different reliability parameters in each column have been assumed in order to observe the influence of failures.

Since the model was build based on the OEE components, and contain parameters of availability, performance and quality, the production value from simulation can be directly used to calculate the OEE indicator.

$$OEE = \frac{Average\ production}{Maximal\ production\ limit} \quad (11)$$

The standard deviation shows the differences between the average value of production and the value of production achieved in each simulation run. For the robotic tended line, the values of standard deviation are also greater because of a much greater production volume and possibility of robots failures. This phenomenon can be explained that absent humans can be replaced but robots not.

TABLE I.
SIMULATION RESULTS FOR MANUALLY OPERATED AND ROBOTIC LINES (average production value P_{avg} in [PCs.] for 50 runs of simulation, α=0,95, MTBFm=500h, MTBFr=1000h, MTTR=4h and MTBFm=1000h MTBFr=2000h MTTR=4h)

	Human Operators	Robots	Human Operators	Robots
	MTBFm=500h MTBFr=1000h MTTR=4h		MTBFm=1000h MTBFr=2000h MTTR=4h	
	Time 8h		Time 8h	
Max Limit [PCs.]	5760		5760	
Average Production P_{avg} [PCs]	1681	4404	1713	4540
Standard deviation [PCs]	50.72	619.3	35.76	440.2
Relative deviation Δ	0.030	0.1406	0.0207	0.0969
OEE	**0,2918**	**0,7646**	**0,2974**	**0,7882**
	Time 24h		Time 24h	
Max Limit	17280		17280	
Average Production	5111	13300	5141	13521
Std. dev. [Pcs]	85.28	1432	84.09	967.6
Relative deviation Δ	0.0167	0.1077	0.0164	0.0716
OEE	**0,2958**	**0,7697**	**0,2975**	**0,7825**
	Time 2000h		Time 2000h	
Max Limit	1440000		1440000	
Average Production	427179	1094949	428765	1127235
Std. dev. [Pcs]	714.96	19331	662.4	12068
Relative deviation Δ	0.0016	0.0176	0.0015	0.0107
OEE	**0,2967**	**0,7604**	**0,2978**	**0,7828**
	Time 6000h		Time 6000h	
Max Limit	4320000		4320000	
Average Production	1281345	3279888	1286457	3379683
Std. Dev. [Pcs]	1207	27496	1306	24189
Relative deviation Δ	0.0009	0.0084	0.0010	0.0071
OEE	**0,2966**	**0,7592**	**0,2978**	**0,7823**

The relative deviation Δ indicates that the proportion of standard deviation to average production value is getting lower for long-time simulations. These effects are related to the occurrence of irregular failures in short-time simulations and to the almost regular occurrence of failures for long-time simulations. Thus simulation time should be greater than or equal to the largest value of the MTBF parameter.

Production throughput of robotic line has increased about 2.6 times comparing to the line before robotization.

The OEE related performance of a production line operated by a robot has improved by 48% comparing to a manually operated line. The OEE indicator equals to OOEh=29.66÷29,78% for humans and OEEr=75,92÷78,23% for robots, for 6000 hours of simulation, and correspond with the values assigned by the theory. Values calculated by theory are: availability of whole robotic system A=0,9085; performance P=0,8333; quality Q=0,9999. That gives OEE=75,7%. Reliability improvement can change the OEE score by about 2%. This shows that reliability parameters have significant influence on the productivity of the production system. Comparing the OEE factors for human operator and robot the greatest improvement is in the performance.

VI. Conclusions

The computer simulation of the simplified model of production line with machines, operators and robots with stochastic (short-time and long-time) reliability parameters allows for better representation and understanding of a real production process. The experiments confirm the advantage of application of robotic operated production lines comparing to manually operated lines. This is particularly to see in the case of work in three shifts for a long period of time. The work organization and robots synchronization play important role and therefore the efficiency of a production line operated by robots has improved OEE indicator by 46-48% comparing to a manually operated line.

Because of irregular work of human operators the buffers (queue) are needed for equalization of production flow and therefore loading (unloading) products from buffers results in low performance of human operators. Also breaks for rest results in lower OEE value.

However, in other cases of machine tools tending, the difference between human operator and robot is not so clearly to see even for long time simulations. The use of OEE factors allows comparing results from other manufacturing systems. The reality is that most manufacturing companies have OEE scores closer to 60%, but there are many companies with OEE scores lower than 45%, and small number of world-class companies that have OEE scores higher than 80%.

There are some place for improvement of availability, performance and quality. Availability depends on planned and unplanned breaks at work. Performance score depend on short machine cycle time and high robot speed. Quality depends on stability of manufacturing process parameters.

Obtained results can be used for detailed design of a robotic workcell and economic analysis, regarding labor costs and costs associated with the investments in robotization.

References

[1] Glaser ,A., "Industrial robots", Industrial Press, New York, 2009.

[2] Hansen, Robert C., "Overall Equipment Effectiveness", Industrial Press, 2005.

[3] Barney, M., McCarty, T., "The new Six Sigma", Prentice Hall Professional, New York, 2001.

[4] Gurel, S., Korpeglu, E. Akturk, M.S., "An anticipative scheduling approach with controllable processing times". Computers and Operations Resesarch, Vol. 37, Issue 6, June 2010, pp. 1002-1013.

[5] Kempa W., Paprocka I., Kalinowski K., Grabowik C., "Estimation of reliability characteristics in a production scheduling model with failures and time-changing parameters described by gamma and exponential distributions". Trans Tech Publications, (Advanced Materials Research; vol. 837 1662-8985), 2014, pp. 116-121.

[6] Paprocka I., Kempa W., Kalinowski K., Grabowik C., "A production scheduling model with maintenance", Trans Tech Publications, Advanced Materials Research ; vol. 1036 1662-8985, 2014, pp. 885-890.

[7] Smith D.J. "Reliability, Maintainability and Risk. Practical methods for engineers", Elsevier, Oxford, 2005.

[8] Paprocka I., Kempa W., Kalinowski K., Grabowik C.: "Estimation of overall equipment effectiveness using simulation programme". Modern technologies in industrial engineering (ModTech2015), 17-20 June 2015, Mamaia, Romania. Materials Science and Engineering ; vol. 95 1757-8981. Institute of Physics Publishing, Bristol, 2015, s. 1-6, doi:10.1088/1757-899X/95/1/012155

[9] Genaidy, A.M., Gupta, T. "Robot and human performance evaluation". In "Human –Robot Interaction" Editor M. Rahimi, W. Karwowski, Taylor & Francis, London, 1992, pp. 4-15.

[10] Nof S. Y. "Handbook of industrial robotics". John Wiley & Sons, New York, 1999.

[11] Kampa A., Planning and scheduling of work in robotic manufacturing systems with flexible production. Ed. B. Skołud: Hueristic Methods of Project and Production Scheduling. Journal of Machine Engineering, Vol. 12, No. 3, 2012, pp. 34-44.

[12] Sakai, H., Amasaka, K., "The robot reliability design and improvement method and the advanced Toyota production system", Industrial Robot: An International Journal, Vol. 34, 4, 2007, pp. 310–316

[13] Hägele, M. Nilsson, K., Pires J. N. "Industrial Robotics", in "Springer Handbook of Robotics". Springer, Berlin, 2008

[14] Dhillon, B.S., Aleem, M.A.,"A report on robot reliability and safety in Canada: a survey of robot users ",Journal of Quality in Maintenance Engineering, Vol. 6 Issue 1, 2000, pp. 61–74.

[15] Baines, T., Mason, S., Siebers, P. O., Ladbrook, J., "Humans: the missing link in manufacturing simulation?", Simulation Modelling Practice and Theory, No 12, 2004, pp. 515–526.

[16] Harriott, C. E., Adams, J. A., „Modeling Human Performance for Human–Robot Systems", Reviews of Human Factors and Ergonomics, No 9, 94, 2013, http://rev.sagepub.com/content/9/1/94

[17] Kulanek, R. "Press Excelence Center COMAU, i.e. robotics press line at the world level", available at www.robotyka.com 2014, (in polish, accessed 15.12.2015).

[18] Woods, D. D. "Modeling and predicting human error", In J. Elkind, S. Card, J. Hochberg, and B. Huey (Eds.), Human performance models for computer-aided engineering Academic Press, 1990, pp. 248-274.

[19] Burduk, A., "Stability Analysis of the Production System Using Simulation Models", Process Simulation and Optimization in Sustainable Logistics and Manufacturing, Springer, 2014, pp. 69-83.