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ANALYSIS OF HUMAN OPERATORS AND INDUSTRIAL ROBOTS PERFORMANCE AND RELIABILITY

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Abstract

In the article problems related to human labor and factors affecting the increasing use of industrial robots are discussed. Since human factors affect the production processes stability, robots are preferred to apply. The application of robots is characterized by higher performance and reliability comparing to human labor. The problem is how to determine the real difference in work efficiency between human operator and robot. The aim of the study is to develop a method that allows clearly definition of productivity growth associated with the replacement of human labor by industrial robots. Another aim of the paper is how to model robotized and manual operated workstation in a computer simulation software. Analysis of the productivity and reliability of the hydraulic press workstation operated by the human operator or an industrial robot, are presented. Simulation models have been developed taking into account the availability and reliability of the machine, operator and robot. We apply OEE (Overall Equipment Effectiveness) indicator to present how availability and reliability parameters influence over performance of the workstation, in the longer time. Simplified financial analysis is presented considering different labor costs in EU countries.

Keywords
human factors, industrial robots, machine reliability, work performance, OEE indicator.

Introduction

Until recently, most of the labor in the industry was done by skilled workers. The industrial revolution caused the replacement of human labor by machinery. But worker was still needed to handle and control machines. Now we observe increasing use of automation and robotization, which replace human labor.

Human labor is still indispensable in many industries, where the assembly of complex products is accomplished. Human has a high flexibility of action, can learn very fast and can work even in the occurrence of significant disruptions. On the other hand, the human is the most unreliable link in a production system. Is quickly bored and tired of monotonous and repetitive tasks. Human can make mistakes (errors) and get sick unexpectedly, or cause disruption in a production process. Therefore, a tendency to replace human work with robots, especially for repetitive and high precision tasks (such as welding), monotonous and demanding physical exertion activities (such as handling of heavy objects) can be noticed.

Robots have mobility similar to human hand, and can perform various complex actions like a human. In addition, they do not get tired and bored. They can work 24 hours a day with the same precision and performance. It is estimated that the application of robots, can decrease production cost by 50%, increase productivity by 30%, and utilization by more than 85% [1].

However, the introduction of robotization requires incurring high costs associated not only with the purchase of a robot, but also with designing and implementation of a workcell and cooperation with a transport system. Robotization will be profitable only in certain circumstances, including; high level of production, work with repetitive and high precision tasks, ensuring the health and safety conditions at work. Such conditions of work occur in the automotive industry and there the most robots are used. Now with the purchasing cost of robots getting lower, the use of robots in other industries also becomes profitable.

The big problem is how to determine the real difference in work efficiency between human and robot. The aim of the study is to develop a method that allows to clearly definite productivity growth associated with the replacement of human labor by industrial robots. In order to assess the effectiveness of the application of robotization in the enterprise we compare production uptime of humans and robots and calculate work efficiency with the use of the OEE indicator (Overall Equipment Effectiveness) that depends on three factors: availability, performance and quality [2]. Another example of this method is presented in publication [3].

Availability and failures

Availability depends on planned work time and unplanned events such as breaks in work and random machine failures, that reduce work efficiency.

In the literature there are two most popular methods for estimating a failure-free time parameter value. The first one uses a fuzzy logic to estimate stochastic parameters and calculate probability of its appearance. The example of using the fuzzy logic to estimate the parameters of a time of a material deficiency and a time of the material deliver is in [4]. The second one uses theory of probability to forecast a value of failure-free time and repair time parameters, under the constraint that a trend based on historical value of the parameter is possible to notice. An example of using normal, exponential, triangular distributions for both failure and repair times is in [5]. In the article [6], 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, three different methods of estimation unknown parameters of the model are proposed. In these approaches Maximum Likelihood Principle, empirical moments and renewal function are used respectively [7]. Next, predictions of the most important reliability characteristics are found using classical regression technique. In the article [8] mathematical model of a production system with failures and the reliability characteristics are given, and numerical examples are attached.

The reliability of objects such as machines or robots, is defined as the probability that they will work properly for a given time under defined conditions of work.

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 [9]:

$$\mathrm{MTTF} = \int_0^\infty t\,\lambda\,e^{-\lambda x}dx = \frac{1}{\lambda}. \tag{1}$$

For repairable objects, the parameters MTBF (mean time between failures), and the MTTR (mean time to repair) are used

$$\mathrm{MTBF} = \mathrm{MTTF} + \mathrm{MTTR}. \tag{2}$$

Machinery failures affect the availability of means of production and can cause severe disturbances in production processes.

Human factors in production processes

Due to a large variety of production processes there are many human factors that are studied from different points of view in area of engineering, biomechanics, physiology, statistics, psychology and philosophy.

Initial researches in the field were conducted by F.W. Taylor, who began systematic observation of human workers. His theory was a starting point to modern production engineering and management. The theory is known as “Taylorism”. It assumes maximal intensification of works, efficient using of operating time and eliminating time waste. Improvement of the economic efficiency, especially labor productivity, was the main aim of this theory.

On the basis of many researches presented in the elaboration [10] it was proved that people have got innate predisposition to different kinds of works, e.g. handwork. Young people are more physically fit and efficient than older people (so called – age effect). On the other hand, older people are characterized by greater professional experience, which allows them to work better and more efficient (experience effect). Also, psycho-physical factors such as, tiredness, illness, mood swings have impact on performed work.

On the other hand, researches on ergonomics are focused on adapting working conditions to the human abilities. The workplace should be designed taking into account the recommendations of ergonomics (e.g. body position, light, temperature, ventilation, noise) to make labor easier.

Regarding to production flow process, people are characterized by high variability of behavior, e.g. when getting tired they are working with lower efficiency. Moreover, people can cause disturbances in production process (human errors). Also, accidents at work may be the result of human errors or equipment failures. These accidents may cause inability to perform future works in production processes.

Since people are very different, there is no universal method for description the interaction between an operator and machine. Most often methods based on the mathematical statistics, e.g. MTM (Methods Time Measurement), are often used to determine working time standards [11].

Also, in computer software for production processes simulation the human factors are not sufficiently utilized. Building a computer model, people are treated as a quasi-technical element of production system and they should operate in the same way as a machine. In practice, human behavior is unpredictable, so it might help to explain why simulation models do not respond to the reality as it would be expected [12].

Knowing categories of human errors can help to simulate human behavior more realistic. Categories of human errors are classified as [13]:

- errors caused by external factors; e.g. an unexpected event, blinding, stunning, consumption of drugs or other factors with an adverse influence on human perception,
- errors caused by internal factors; e.g. reduced perception, incorrect assessment of situation, concentration lack, insufficient professional experience and ignorance of the danger.

As a result of these factors some errors can occur:

- incorrectly performed action/operations (repeated actions required),
- omission of performing an action/operation,
- wrong recognition of problems and performing an incorrect action/operation,
- performing of prohibited action/operation (it results in product errors, machine failures or accidents/injuries).

The possible effects of human errors are:

- delay in production process,
- stop of production process,
- defective product – requires additional time to repair or production of an extra piece of product for replacement,
- defective batch of products – requires warranty repair,
- machine failure – production stop on a single machine or whole production line,
- accident – one victim,
- catastrophic failure – many victims, a lot of damages in property.

From the other hand, periods of employee's inability to work, e.g. due to labor laws, should be accounted for better modelling of human behavior. Taking into consideration the employee availability to work in the production system, the planned and unplanned downtimes can be classified:

- micro-downtime, less than 1 min – e.g. as a result of distraction,
- short downtime, about 1–15 min – e.g. physiological needs,
- rest and meal periods, 15–30 min,
- lateness for work, from a few minutes to hours,
- minor injuries requiring a paramedic assistance, a few minutes,
- inability to work – illness, accident – (an average 10 days per year),
- vacation leave – from 20 to 30 days per year, (depending on the law of the country),
- unexcused absence from work,
- public holidays – statutorily days off,
- strike, protest, refraining from work.

In summary, the human factors are unpredictable and lead to destabilization of production processes. Most often they are analyzed selectively, e.g. minor injuries are not notified as the accident, short downtimes such as a change of used or damaged tool are not treated as a failure, etc. The diversity of human factors mentioned above, strengthen difficulties of modelling and parameterization of the production process.

Human reliability parameters assumption

Let us consider the situations when the human operator handles machine manually for example hydraulic press or machine tool. Deterministic operation work times are used in the production planning process. We also assume a mechanistic model of operator and incorporate elements of queuing theory. In the queuing theory, inter-arrival times between tasks and service times are described using random variables.

The initiate time of subsequent tasks is described using the exponential distribution. Work time is described by a normal distribution with mean value of work cycle T_c and standard deviation δ_c. The work cycle time consists of constant time T_m of machine work cycle and random variable time of manual work cycle T_p

$$T_c = T_m + T_p. \tag{3}$$

Planned working time of the human operator can be represented by using a schedule, including the planned interruption of work such as: preparation of workstation, set up, testing of machines, cleaning after work completion and meal breaks and rest pause. Planned vacations and excused absences can be omitted because replacement can be arranged.

We take into account unplanned interruptions at work: short-term interruption resulting from a variety of psycho-physical conditions, for example, physiological needs and long-term interruptions associated with sudden disease or accident.

We can model them as machine failures, and describe using exponential distribution with a constant failure rate. Considering the average length of human absence because of health problems 2x5 days per year and 250 working days per year [14], the probability of an employee absence can be described using the parameters MTBF = 125 days and MTTR = 40 hours. In turn, short-breaks are difficult to estimate because of human individuality and can be approximated using the parameters MTBF = 4–8 hours and MTTR = 5–10 minutes.

Robotic factors in production processes

Modern industrial robots are characterized by the precision of operation, high speed of motion and reliability of work. Robots can be equipped with different tools and used to different works that were traditionally performed by people. It is important, that robots can work in conditions harmful to human health. Before starting an automated process, the robot should be programmed by operator who used teaching method or off-line created programs.

Robots are used to perform strictly defined tasks. Most of them don't have sensors and cannot react to disturbances of the production process. The serious problem is that robots are operating "blindly" and are not able to recognize people, machines, wrongly placed parts and identify all anomalies in their own functioning. Therefore, robotic processes must be supervised and automated robotic cells should protect workers in accordance with the safety rules and regulations [1].

Nowadays, some new-generation robots occur in the market. They 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.

Theoretically, the robots can work 24 hours per day without breaks, but human supervision of the production process is necessary. Changes of tools and reprogramming require participation of the operator. Moreover, robot requires periodic maintenance service and proofing the correct functioning before each automatic run.

Robot reliability parameters

The life cycle of robot is estimated at about 10–15 years. Results of the research on reliability of industrial robots at Toyota are presented in article [15]. Failure rate curve for conventional robots and new robot generation are presented in Fig. 1. For the first type of robots (Unimate) uptime was equal to MTBF = 500 hours. The next generation of robots was characterized by MTBF about to 8000 hours [1]. Now robot manufacturers declare average MTBF = 50000–60000 hours (or even 120000 hours for SCARA robots) or 20–100 million cycles of work for light loads and 5–40 million cycles for heavy loads [16]. However, the robot's equipment is often custom made, therefore, this data may turn out to be unreliable.

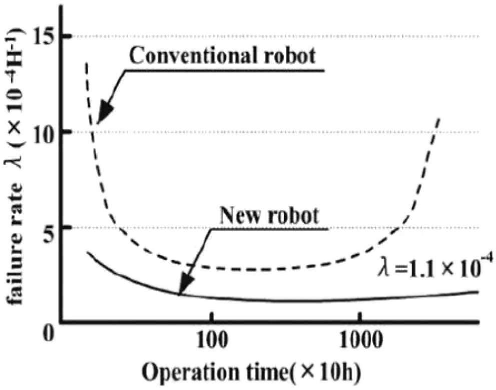

Fig. 1. Failure rate curve for conventional robots (first generation) and new industrial robots [15].

Work efficiency and OEE

The OEE (Overall Equipment Effectiveness) is used to evaluate work efficiency and the utilization of the means of production. The OEE metric consists of three factors: availability, performance and quality [2]

$$\text{OEE} = (\text{Availability}) \times (\text{Performance}) \times (\text{Quality}). \tag{4}$$

The term of availability concerns the ratio of the time spent on the realization of a task to the scheduled time

$$\text{Availability} = \frac{\text{available time} - \text{failure time}}{\text{scheduled time}}. \tag{5}$$

The performance is the ratio of the time to complete a task under ideal conditions compared to the realization in real conditions. The term of performance can be also defined as the ratio of the products obtained in reality to the number of possible products to obtain in the ideal conditions. The performance is reduced (loss of working speed) when any disturbances occurs e.g. human errors

$$\text{Performance} = \frac{\text{ideal cycle time}}{\text{real cycle time}}. \qquad (6)$$

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

$$\text{Quality} = \frac{\text{good product}}{\text{overall product}}. \qquad (7)$$

In the case of large scale production, the number of good products is a random variable, which can be described by a normal distribution with standard deviation. Quality levels are determined by ranges of standard deviation (described by sigma parameter). In traditional manually-operated production systems the level 3 sigma is considered to be sufficient. While in the modern automated and robotic systems it is possible to achieve the level of 5–6 sigma [17].

Taking into account the above, Qh = 99.73% can be assumed for hand-operated tasks quality index and Qr = 99.999997% for robotic station.

Work schedule

A typical work schedule of the machine consists of set up activities, operation time and close down activities. A typical work schedule of an operator consists of some organizational activities at start of the shift. All humans have meal break and rest pause in the middle of a shift. At the end of the shift cleans a workstation and some organizational activities are required.

In the case of the application of SMED method (Single Minute Exchange of Die) setup activities take about 10–15 minutes. Employee is entitled to at least 15 minutes break at 8 hour working day. Taking into account the organizational activities and random breaks at work, it is estimated that the real working time for machine operator is approximately 7.5 hours.

Robot scheduling problems are described in [18]. For the robot it is required about 10–15 minutes for setup activities and testing a new program, however, the robot can work without any break until the next changeover.

The availability of the workstation is also reduced by short and long-term failures, that are difficult to predict, and therefore sometimes production planning diverge with the realization of production. Because it is impossible to conduct experiments on a real production system, computer simulations model was built in order to analyze the efficiency of the production system.

Example – hydraulic press workstation

The above presented problem is analyzed for the hydraulic press workstation. Presses are often used in various production processes e.g. pressing, sheet metal forming etc. The visualization of the workstation is presented in the Fig. 2.

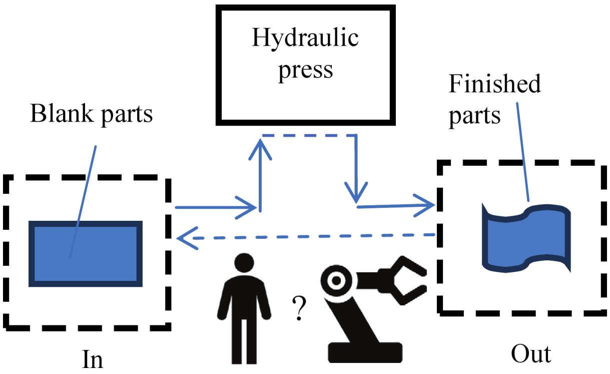

Fig. 2. Visualization of hydraulic press workstation.

Simulation models were developed in Enterprise Dynamics 9. This software allows for computer modeling and simulation of discrete production processes with the use of human resources as well as robots.

Computer models of manually operated workstations as well as operated by a robot, have been developed. The planned breaks at work and failure rates were introduced into the models. The model consists of the following objects: the input (Source), storage buffers (Queue), machine, operator (Human Resource) or robot, output elements for good products (Good parts) and defective products (Bad parts) and controls objects (Availability control, Schedule, MTBF, MTTR). The model of the human operated workstation after 8 hours of simulation is presented in the Fig. 3.

The model of robot operated workstation after 6000 hours of simulation is presented in the Fig. 4.

It was assumed that simulation takes 1, 2 or 3 shifts by 250 working days per year. Since human operators work with variable performance in order to determine the time parameters needed to handle a single job, a collaborative study involving the time study for one work hour on a test workstation was performed, similar to the test described in [19].

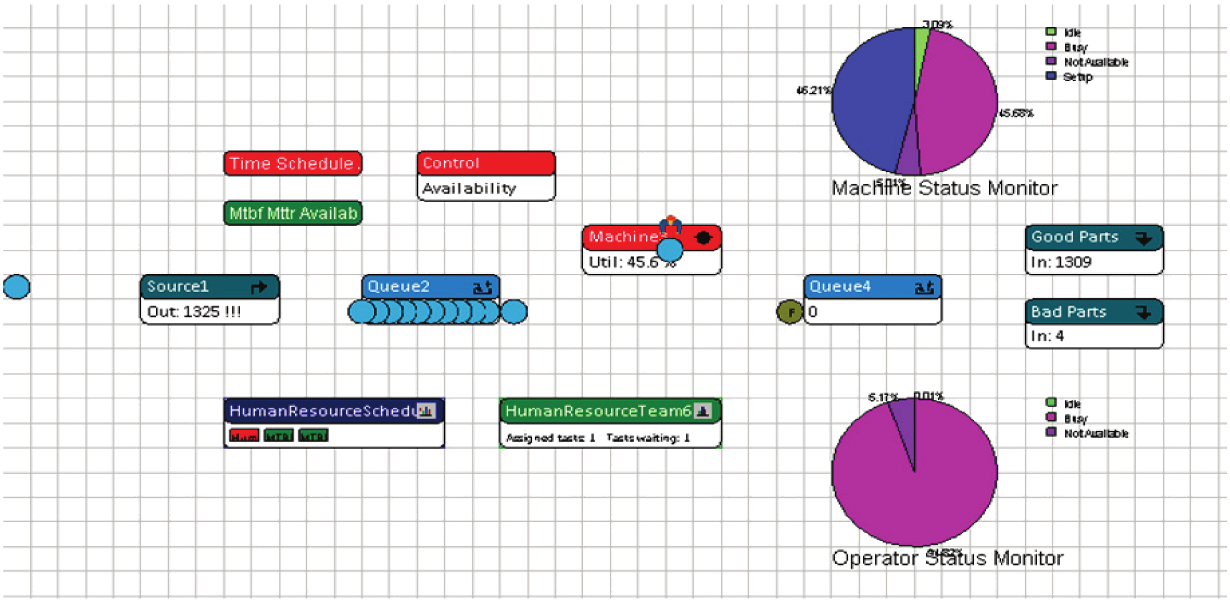

Fig. 3. Model of human operated workstation after 8 hours of simulation.

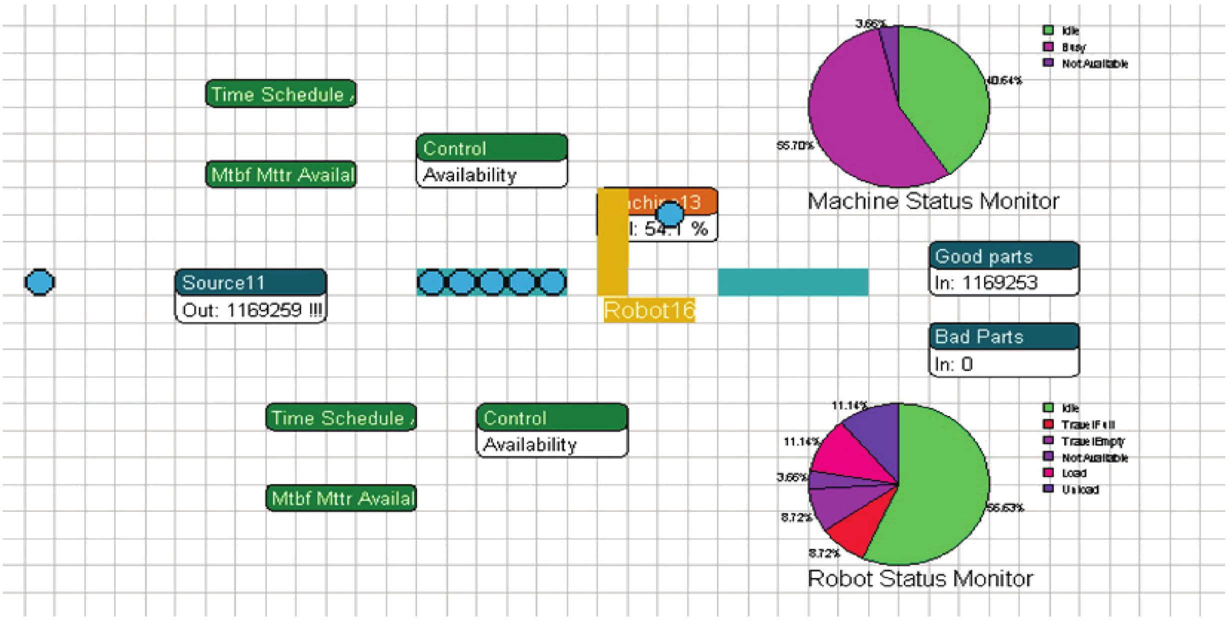

Fig. 4. Model of robot operated workstation after 6000 hours of simulation.

Uniform flow of tasks and $T_m = 10$ seconds, and constant processing cycle for the machine were assumed. On the basis of the time measurements obtained for the human operated workstation, normal cycle time was determined to $T_c = 20 \pm 1$ seconds, which corresponds to production yield $P_h = 3$ pcs/min. From relationship (3) it means that the operator cycle time is equal $T_p = 10 \pm 1$ seconds.

For comparison, the cycle time for robotic workstation was also measured, and constant cycle time of $T_r = 16.5$ seconds was obtained, which corresponds to production yield of $P_r = 3.6$ pcs/min.

Performance can be defined in relation to the minimum machine work cycle $T_{\min} = 10$ seconds, which corresponds to maximum productivity $P_{\max} = 6$ pcs/min.

Taking into account the relationship (6) the performance index is calculated as follow:

- the performance of the human operated workstation $Hperf = 10/20 = 0.5$,

- the performance of robot operated workstation $Rperf = 10/16.5 = 0.61$.

A fixed work schedule for one shift was assumed, namely: setup time at the beginning of the shift = 10 minutes, meal and rest break = 15 minutes, close down time at the end of the shift = 5 minutes.

Short and long-term unreliability of machines and workers are assumed.

Hydraulic presses (heavy duty) are characterized by relatively high failure rate by [20] and, therefore, the $MTBFm1 = 100$ hours and $MTTRm1 = 4$ hours are assumed. There may be quite often a short downtime associated with the product jam in the die and therefore $MTBFm2 = 8$ hours and $MTTRm2 = 5$ minutes are assumed.

For the operator an average of 10 days (2 × 5) of the period of inability to work is estimated which corresponds to $MTBFh1 = 1000$ hours and $MTTRh1 = 40$ hours. Short-term interruptions associated with physiological needs $MTBFh2 = 8$ hours and $MTTRh2 = 5$ minutes, are also assumed.

For the robot with accessories, $MTBFr1 = 8000$ hours and $MTTRr1 = 8$ hours are assumed.

For the data set the theoretical value of OEE has been calculated:

- for the workstation operated by the Human $OEEh = 43\%$,
- for the workstation operated by the robot $OEEr = 56\%$.

Next, a number of computer simulations covering the time from 8 hours to 250 working days, in order to notice the influence of long-term failures on the production efficiency, were performed.

Simulation results

The production yield P obtained in the simulation is a random variable, which is composed of several exponential distributions. For a long simulation time this distribution is ever closer to a normal distribution, but presents some asymmetry.

$$P = W(T - T_a - T_b) - B, \qquad (8)$$

where W – production efficiency – pieces per time [pcs/h], T – system work time [hours], T_a – the sum of non-overlapping failure times ΣT_{ai} for all system components [hours], T_b – the sum of non-overlapping planed downtime ΣT_{bj} for all components of the system, B – the number of defective products [pcs].

The random nature of the failures causes a significant dispersion of obtained values (relatively large standard deviation for confidence level $\alpha = 0.95$). Average production results obtained from simulation experiments are summarized in the Table 1.

Table 1

Simulation results for human operator and robot (average production [pcs.] for 100 runs of simulation, confidence level $\alpha = 0.95$).

	Human operator	Robot
Time 8 h		
Max Prod. Limit [pcs.]	2880	2880
Average Production [pcs.]	1279	1642
Standard deviation [pcs.]	178	98
OEE	0.4441	0.5701
Time 24 h		
Max Prod. Limit [pcs.]	8640	8640
Average Production [pcs.]	3734	4890
Standard deviation [pcs.]	537	387
OEE	0.4322	0.5660
Time 2000 h		
Max. Prod. Limit [pcs.]	720000	720000
Average Production	311046	407055
Standard deviation [pcs.]	3957	4336
OEE	0.4320	0.5654
Time 6000 h		
Max. Prod. Limit [pcs.]	2160000	2160000
Average Production [pcs.]	931791	1222770
Standard deviation [pcs.]	5798	6830
OEE	0.4314	0.5661

There are results of four experiments with different simulation time. Each experiment consists of one hundred simulation runs.

Because the models were build based on the OEE components, the production yield from simulation can be directly used to calculate the OEE indicator from equation (9)

$$\mathrm{OEE} = \frac{\text{Average production from simulation}}{\text{Maximal production limit}}. \qquad (9)$$

The value *Maximal production limit* determines the maximum possible production volume in a given period of time at the ideal working conditions.

The standard deviation shows how big differences between each simulation run are. In the two first experiments with short simulation time, greater influence of human random failures can be noticed and therefore standard deviation of human operated workstation is greater than in the robotic line. In the two next experiments with long simulation time, the influence of long-term robot failures can be observed and therefore the standard deviation of robotic line is becoming high.

The use of robot operated workstation has improved productivity for about 30% in relation to the productivity achieved by human supported workstation. The OEE indicators obtained for 6000 hours simulation are OEEh = 43.1% for human operated workstation and OEEr = 56.6% for robot operated workstation and correspond with the values assigned before by the theory.

Due to the high costs associated with the robotization of manufacturing processes, financial analysis of investments is required.

Financial analysis

Currently the prices of industrial robots are relatively high, but are steadily falling, while the labor costs systematically grow. Increasing of the minimum wage and the average wage of workers across the European Union can be observed [21]. Therefore, in some situations, the costs of robots may be lower than the labor costs, especially in the most developed countries.

However, we should notice that the cost of buying a robot is only part of the costs associated with an investment in the robot workstation. Analysis of the cost of investment in robotization is difficult, because the robotic system requires also additional elements. Therefore, the analysis must include a variety of cost factors. Basing on the publication [22], it can be estimated that the cost of buying the robot is only about 50% of the total investments in robotic workstation (Table 2).

Table 2
Estimated investment cost of typical medium size robotic workstation [22].

Cost elements	Cost percentage
Industrial Robot	50%
System engineering	15%
Project management	5%
Tooling	5%
Peripherals	5%
Software	5%
System Integration	10%
Training	5%
Total cost	**100%**

Each time, a detailed design of robotic workstation is required and adaptation to the conditions of a specific plant. A robot is a machine with high degree of universality, but the possibilities of its application is determined by specific equipment, tools and grippers. It is often special equipment, which requires an appropriate design and implementation. There is a need for integration of all elements of the robot workstation, especially the robot control system and other enterprise systems. An important element is additional software for robot programming in off-line mode. The last step is staff training.

In typical cases, the capital expenditure related to the project and implementation of robotic workstation (with special equipment) may be the same as the cost of buying a robot only. Regarding the high financial effort related with robotization, one should carefully consider the cost-effectiveness of such an investment and should be aware that the unusual implementation may be associated with much higher costs.

The market prices of industrial robots are very diverse. Prices of small robots begin from about 20000 euro, medium size robots 40000–80000 euro, large and heavy-duty robots cost about 300000 euro or more [23].

The relationship of typical robot workstation cost (total cost 100000 euro) to the annual labor cost in some EU countries is presented in the Table 3.

Table 3
The relationship between typical robot workstation cost (total cost 100000 euro) to the annual cost in selected EU countries, based on [21, 22].

	EU-28	Germany	Spain	Poland
Average annual cost per employee in industry sector [EUR]	65200	77600	46600	17000
Ratio of robotic workstation cost (100000 EUR) to annual cost of one employee	1.53	1.29	2.15	5.88

An approximate evaluation of the investment's profitability can be made using the payback period from the investment T_r, which can be calculated from equations (10) or (11) [24]:

$$T_r = \frac{I_n}{l_s(l_p - l_o)k_p - (r+p)I_n}, \tag{10}$$

or

$$T_r = \frac{I_n}{l_s(w - l_o/l_r)k_p - (r+p)I_n}, \tag{11}$$

where T_r – payback period [Year], I_n – investment expenditures [EUR], l_s – number of working shifts (1, 2 or 3), l_p – number of employees replaced by robot on one shift (1 or more), l_o – number of employees serving a robotic workstation ($l_o = 0.2$–1, one operator can handle several robotic workstations), k_p – average annual labor cost of one employee [EUR/year], r – discount rate, p – share of the robot's annual operating cost as a percentage of capital (amortization), w – increase rate of robot work efficiency compared to 1 employee efficiency, l_o/l_r – number of employees serving robots in relation to the number of robots.

The sum of the labor cost of employees, who were replaced by the robot is cost saving and can be treated as return from investment. The shorter the payback period, the faster the return from investment. In the best situation, the payback period is about 1 year, and it is assumed that the limit value of the refund period is about 3–5 years.

Example:

The costs of robotization of hydraulic press workstation were analyzed. It can be manually operated by a single employee per shift or by industrial robot that can run continuously three shifts per day.

Typical financial data were assumed:

- investment expenditures $I_n = 100000$ [EUR],
- number of working shifts $l_s = 1$, 2 or 3
- average annual labor cost of one employee in EU countries (Table 3),
- discount rate $r = 0.05$,
- share of amortization $p = 0.2$,
- increase rate of robot work efficiency compared to 1 employee efficiency $w = 1.3$ (according to results obtained from simulation experiment),
- number of employees serving robots in relation to the number of robots $l_o/l_r = 0.2$.

Obtained results are presented in the Table 4.

Table 4
Payback period T_r for hydraulic press robot workstation [Years].

Robot payback period T_r [years]			
Country	Working shifts		
	1	2	3
EU-28	2.14	0.84	0.53
Germany	1.66	0.69	0.43
Spain	3.81	1.29	0.78
Poland	−15.87	8.06	3.22

A great difference of payback period between high developed countries like Germany and less developed countries like Poland can be observed. This depends on different labor cost in analyzed countries. The payback period is also related with robot efficiency and number of replaced employees. The effect is greater when the robot is working for two or three shifts.

Conclusions

In the paper a computer simulation method with sophisticated models of the operator and the robot operated workstation were used in order to better present the real production processes. The performance of the work cells was compared, which pretty well reflect the real process of production. As it was predicted, the robot achieves much greater performance then human operator and is more reliable especially in the long time and therefore robotic workstation achieves significantly higher productivity.

Due to the high costs associated with the robotization of manufacturing processes, financial analysis of investments plays important role. Presented simplified financial analysis show that robot implementation profitability is depended on varying labor cost in different countries.

Obtained results can be used for detailed design of a robotic workcell and for more detailed analysis of costs related with robotization.

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