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planning, scheduling,
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PLANNING AND SCHEDULING OF WORK IN ROBOTIC MANUFACTURING SYSTEMS WITH FLEXIBLE PRODUCTION

Industrial robot are more and more used in industry because of their speed and accuracy. Robots can work 24 hours a day, but for best performance the robot movements must be planned in detail. In the article the problem of planning and scheduling of robotic work is described. An example of robotic system with three machines is given and analysed. Simulation model of the robotic system is also presented. On basis of the simulation model some simulation experiments have been carried out. Robots work best in determined production conditions. In experiment the influence of flexible production with variable production conditions on robotic system performance has been studied. Carried out simulations show influence of robot speed and machines work time on the system productivity. Also the bottleneck effect has been studied.

1. INTRUDUCTION

Industrial robots are becoming more widely used in the industry to perform a variety of work. There is a wide variety of uses of robots and various configurations of robotized work stations. Most commonly they are used for welding, gluing, as well as for transport, manipulation of the details, and to load/unload machines [7]. Robots can work much faster and more efficiently than humans and can work 24 hours a day. They also can perform repetitive and monotonous activities much more accurately than people. On the other hand people are more flexible and respond better to different distortions [5].

Robots work best in determined production conditions, when all the time are the same products at permanent process parameters. E.g. for correct operation of the robot is required to load and put off details always from the same place. This requires the appropriate organization of work and the preparation of the transport system.

The advantage of the robot is easier changeover of equipment and the ability to perform a variety of work programs that can quickly change the production profile.

Currently manufacturing flexible as possible in order to better respond to the needs of the market is being sought. For this purpose, flexible production systems are characterized by the possibility of producing a wider range of products. An example is the simultaneous production of several types of similar products on flexible robotic line or cell.

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Because of the various process parameters for different products there is the problem of planning robot move sequence and the problem of scheduling the parts for maximum efficiency. This problems should be to consider at the design stage of robot station to provide the required performance [1],[2],[3].

Designing of a robotic station is a complex problem. There are various issues related to the selection of a robot, placement of the required workstation, design of the robot trajectory, programming robots. Choosing or designing appropriate robot gripper or tool that determines the possibilities of its application is also required [7].

Assuming that we know the initial design of the robotic system and data of manufacturing process, the goal is to define a work plan and a schedule to determine the desired performance.

2. PROBLEM ANALYSIS

In the literature many different scheduling problems of robotic work are described [1],[2],[3]. They differ in configuration that is, for example: the number of robots and machines, the characteristics of the work and the number of manufactured products. For some configurations, for example, systems with individual robots and one kind of product it is possible to obtain optimal scheduling algorithms (simple robotic objective) [3]. For systems of robotized work stations with different parts and for the number of machines $m \geq 3$ (robotic objective with multiple part-types) the scheduling problem is NP-hard, and there is no known optimal solution [2],[3].

Classification of robot scheduling problems [3]:

- Single robot – multiple robots,
- Single part – multiple parts,
- Simple machines – parallel machines,
- Single gripper – dual gripper,
- Free pickup – blocking,
- No wait –wait interval,
- Travel metric A, C, E.

From the point of view of the production process, industrial robots can perform two functions:

a) may perform the functions of transportation and handling, and can for example, operate the machine (eg machine tools, presses, die casting machines, etc)

b) or the same robot can be equipped with a machine tool, and can perform some technological operations (eg welding, machining).

A) The robot work is composed with loading an item from the store entrance (input), the movement in the proximity of the machine, precision setting on the machine holder. Then after the machine operation robot receives the processed item from machine and moves it to another station or to store (output). Due to the high rate of speed one robot can operate several machines. These machines can be placed in series and in sequence (simply machine) or parallel. In addition to the movement of cargo robot performs also the empty return movements to get another load. This requires special gripper.

B) Production part is delivered to robot station. Then robot can operate in complex three dimensional space. After operation part is transported out and next part is delivered. A more complex operations will require the participation of several robots that will work sequentially or simultaneously. Transport can then be implemented using linear conveyors, trolleys or other robots.

3. EXAMPLE OF ROBOTIC CELL

We are considering automated work cell containing 3 machines running sequentially (M1, M2, M3), input station (M0) and output station (Mm + 1) supported by the angular robot (Fig. 1) [2]. The product must move sequentially through all positions. The product is moved using a robot that performs several types of operations. They are: gripping the part (load), the movement with the cargo (travel full), unloading the part (unload), displacement without cargo (travel empty.) Robot movement time depends on the distance between the positions and the speed of the robot and may be about few seconds. Time of loading and unloading the robot depends on how a gripper and manipulation object are fitting in positions and can range from few to several seconds. Waiting time on the machine availability or product delivery due to various disturbances can also occur.

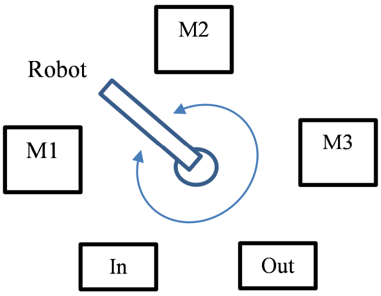

Fig. 1. Schema of robotic cell

This robotic cell is containing single robot with simple machines, single gripper, transport with blocking, wait interval and constant travel time.

Mode of action of the robot can be plotted using cyclograph (Fig. 2). Consider the steady-state, in which all the machines work. Because it does not have buffers, unloading machines is possible if next position is free. Otherwise, this instance is blocked because the robot gets the item, which may not be put anywhere else. Because the only output is always free, the robot work cycle can start from unloading the last machine (1. M3-> Out). Then arises the possibility of transporting the item from the machine M2 to M3 (2. Travel empty Out-> M2, 3. Travel full M2-> M3). Similarly are implemented the following movements of the robot. A complete cycle of work includes 8 moves and is shown in Figure 2. The work cycle is characterized by resistance to interference, but there are also other cycles possible.

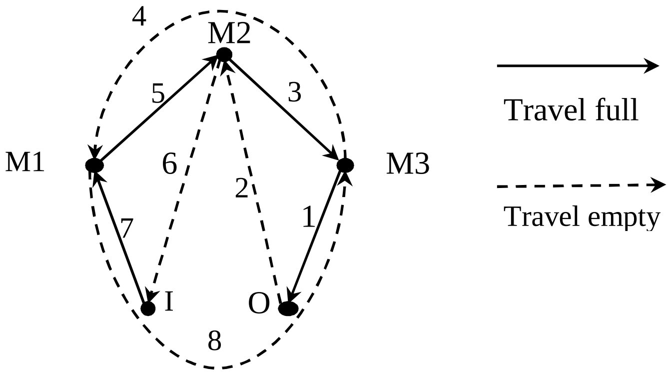

Fig. 2. Robot move cycle

It can also be represented as sequence of movements:

M3 ⇒ O → M2 ⇒ M3 → M1 ⇒ M2 → I ⇒ M1 → M3

Symbol (⇒) represents travel full and (→) travel empty.

Robot work cycle can be described shorter using a sequence of movements with the cargo, because the empty movements can be deduced. Assuming that we start move from loading parts from machine Mi, where i = {0, 1, 2, 3} (and that this machine was previously running) robot move cycle C can be represented in the form of four numbers.

C = (3, 2, 1, 0) or (0, 3, 2, 1)

There are also other possible work cycles, e.g. (0, 1, 2, 3), (0, 2, 1, 3), (0, 1, 3, 2), (0, 3,1, 2), (0, 2, 3, 1) [2],[3].

Which versions of the cycle is the best, it will depend on how the cell works and, above all, from the working time of machines. Machine with the longest working time will be a bottle neck and should be supported by the robot in the first place.

Sample schema of robot work cycle is shown in Figure 3.

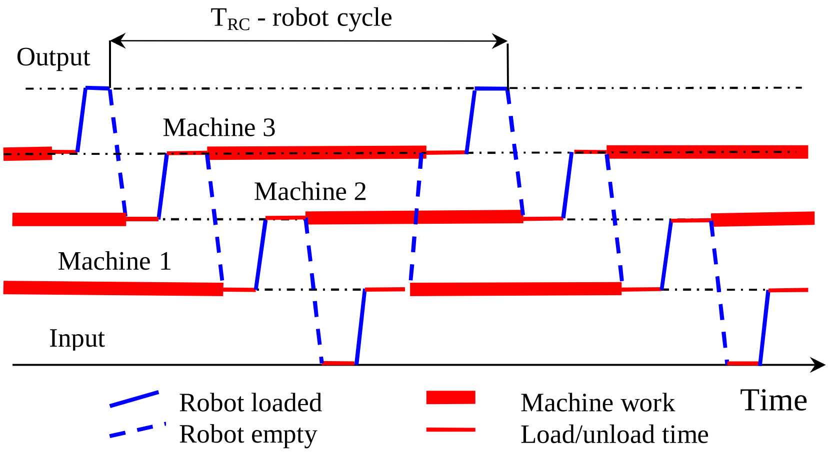

Fig. 3. Fragment of robot work cyclograph

If the machines and robot work time will be constant then robot work cycle will also be settled [2].

Robot cycle time T_{RC} can be estimated based on dependencies:

$$T_{RC} = \sum_{1}^{m+1} t_{load} + \sum_{1}^{m+1} t_{unload} + \sum_{1}^{m+1} t_{full} + \sum_{1}^{m+1} t_{empty} + \sum t_{Rwait} \tag{1}$$

Where *m* is the number of machines requiring maintenance.
Robot activities time:

- t_{load} – load time,
- t_{unload} – unload time,
- t_{full} – travel full time,
- t_{empty} – travel empty time,
- t_{Rwait} – robot wait time.

Cycle time of production part T_{pc} can be estimated on the basis of the formula 2:

$$T_{PC} = \sum_{1}^{m+1} t_{load} + \sum_{1}^{m+1} t_{unload} + \sum_{1}^{m+1} t_{full} + \sum_{1}^{m} t_{m} + \sum t_{Mwait} \tag{2}$$

Where t_m is the work time of machine and t_{Mwait} is the wait-time to deliver or receive the product by the robot. Formulas 1 and 2 are different because the robot and the machine can work parallel, for example, when the robot performs the return move (travel empty) machine can perform operations on the parts.

Productivity P (yield) and production efficiency is related to the length of the robot cycle. If it is shorter than better performance can be achieved.

$$P = \frac{3600}{T_{RC}[s]} \left[{}^{parts}/_{hour}\right] \tag{3}$$

Robot utilization U_R can be determined as the ratio of the working time of the robot (without breaks) to cycle of robot T_{RC}.

$$U_R = \frac{\sum t_r}{T_{RC}} 100\% = \frac{T_{RC} - t_{Rwait}}{T_{RC}} 100\% \, [\%] \tag{4}$$

Machine work utilization Um can be determined as the ratio of the working time of the machine to robot cycle time.

$$U_M = \frac{\sum t_M}{T_{RC}} 100\% [\%] \tag{5}$$

The duration of the motion of the robot can be calculated based on the distance between the positions and the movement speed of the robot.

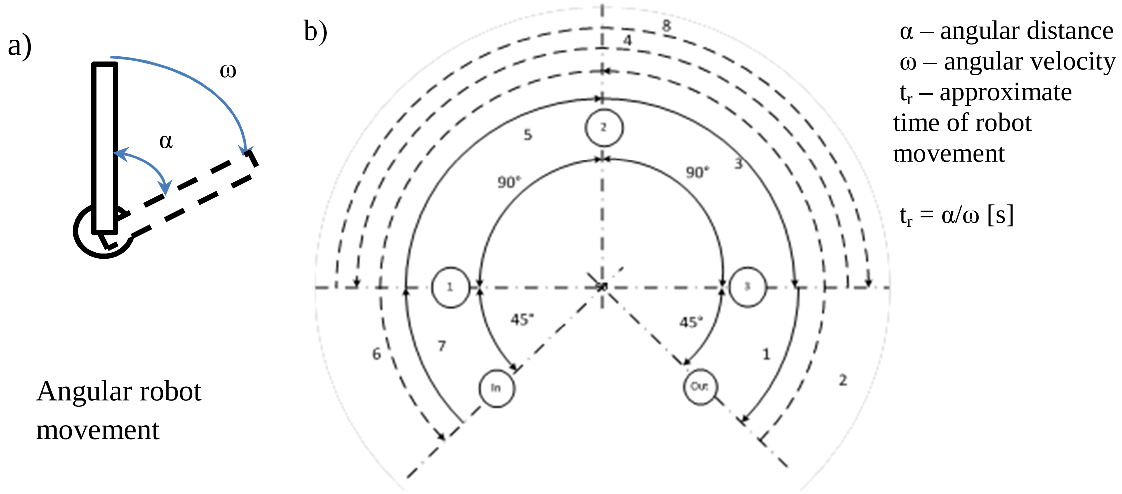

Fig. 4. a) Movement schema of angular robot, b) robot movement cycle

Due to the very large acceleration achieved by modern robots the phase of acceleration and braking can be skipped, because it lasts very short [7]. Assuming the angular distance between the robot positions as in Figure 4, the distance that the robot must travel during one working cycle can be specified.

By analysing the figure above we notice that the empty movements of robot require to overcome greater distances than the movements with the load. Assuming a typical angular speed of robot ω = robot 90 °/s, the travel times of robot movements can be easily calculated.

$$T_{full} = t1 + t3 + t5 + t7 = 0{,}5 + 1 + 1 + 0{,}5 = 3 \text{ [s]} \quad (6)$$

$$T_{empty} = t2 + t4 + t6 + t8 = 1{,}5 + 2 + 1{,}5 + 2 = 7 \text{ [s]} \quad (7)$$

Assuming the loading and unloading time is equal $t_{load} = t_{unload} = 3$ s and having regard to four loading and unloading operations we can estimate the minimum robot work cycle on the basis of the formula 1.

$$T_{RCmin} = 4 \cdot t_{load} + 4 \cdot t_{unload} + T_{full} + T_{empty} = 4*3+4*3+3+7 = 34 \text{ [s]} \quad (8)$$

If machine operating time will be longer than the work cycle of the robot then waiting occurs at the end of the machine work and this cycle time will increase accordingly. If machine runtime will be less than approximately 19 s then an waiting on machine for handling by robot will occur. On the basis of designated robot work cycle the system productivity and performance of the robot can be estimated.

$$P = \frac{3600}{T_{RC}[s]} \, [{}^{parts}/_{hour}] = \frac{3600}{34\,s} = 105{,}8 \, [{}^{parts}/_{hour}] \quad (9)$$

Theoretically without interruptions and delays robot utilization can achieve 100% and machine utilization about 55% for this data example. When machine work time will be longer then 19s, the machine utilization will be higher but on other hand robot utilization will be lower.

Because, in practice, there are a variety of distortion and imbalances of machines work the real productivity will be lower. In the case of simple systems, we can specify how the work is done in this way of simply analysis.

Now often production is flexible to manufacture different versions of the product in order to meet the diverse needs of customers. This, however, increases the complexity of the control of the manufacturing system. In this case the complex analytical solution becomes very difficult, but computer simulation software can be used as support.

4. SIMULATION MODEL OF ROBOTIC WORKCELL

For the analysis of the case described earlier a Enterprise Dynamics simulation model has been developed. This software allows to model a variety of complex industrial processes [6]. It also enables simulation of production processes for different values of the parameters of stochastic or deterministic processes, and provides a visualization of the production. The possibility of simultaneous flexible production of two different products through the robotic system has been assumed. The model of the robotic cell shown in Figure 3, consist of one robot, three machines, two inputs with different products, buffer storage and output.

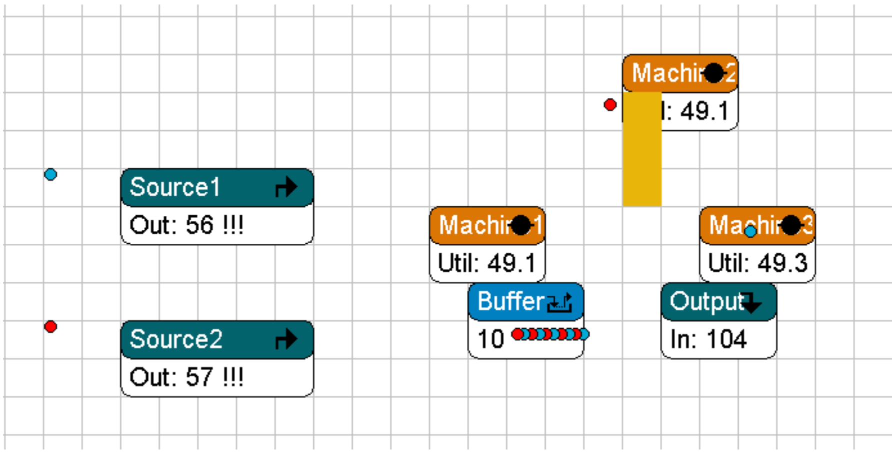

Fig. 5. Computer model of robotic cell

The behaviour of the model of the robot cell with data as in the previous example was studied. Different values of time machines were given, in order to determine the maximum productivity of the system. Maximum productivity 104 parts/h have been obtained for a machine work time *Tm* = 17s. This value is not much different from the calculated theoretically yield of maximum 105parts/h. Differences may result from the rounding of certain values. Report of the simulation indicates the average time period the parts stay on the machines is about 18-19s (Tab. 1) and a small blocking of machines due waiting to access of the robot (Fig. 7).

Theory of constraints (TOC) claims that each production system has at least one bottleneck resource and the bottleneck determines throughput of the whole system [4]. The bottleneck may be robot, machine, buffer or source.

Tab. 1. Simulation report after one hour of work

Station name	content		throughput		average stay time
	current	average	input	output	
Source1	1	0.836	57	56	52.772
Buffer	10	9.855	113	103	326.417
Machine1	0	0.572	104	104	19.793
Machine2	0	0.536	104	104	18.547
Machine3	1	0.550	105	104	18.981
ROBOT_1	1	0.776	415	414	6.735
Source2	1	0.834	58	57	52.312

The relationship between machine work time and production is shown on the Fig. 6. The machine time was changed each case but the times were equal for all machines.

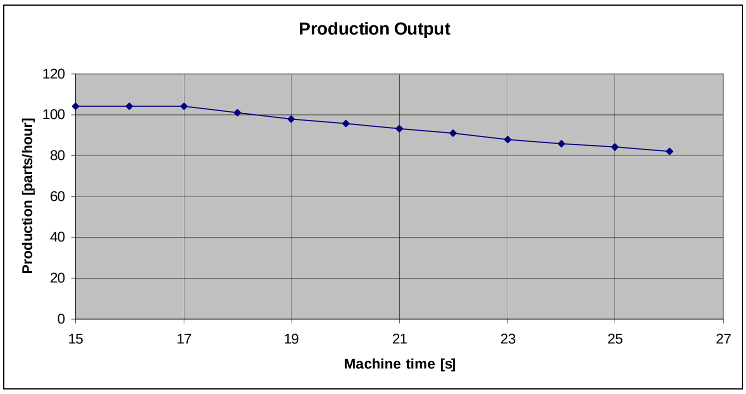

Fig. 6. The relationship between system productivity and work time of machines

Results show that for machine time less or equal to 17s, the robot is the bottleneck. For machine time higher then 17s, bottlenecks are the machines.

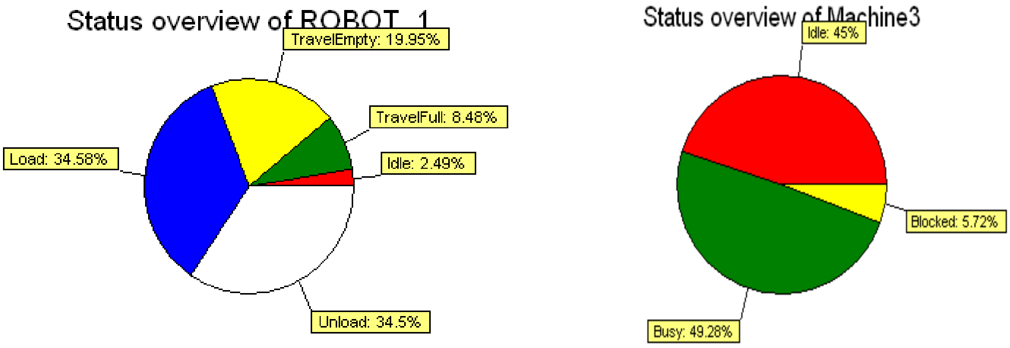

Fig. 7. Work status of Robot1 and Machine3

Manufacturing process can be also analysed at the Gantt chart covering the execution of 3 parts presented below (Fig. 8). From the chart the production cycle of the parts can be designated, which is T_{cp} = 84-85s.

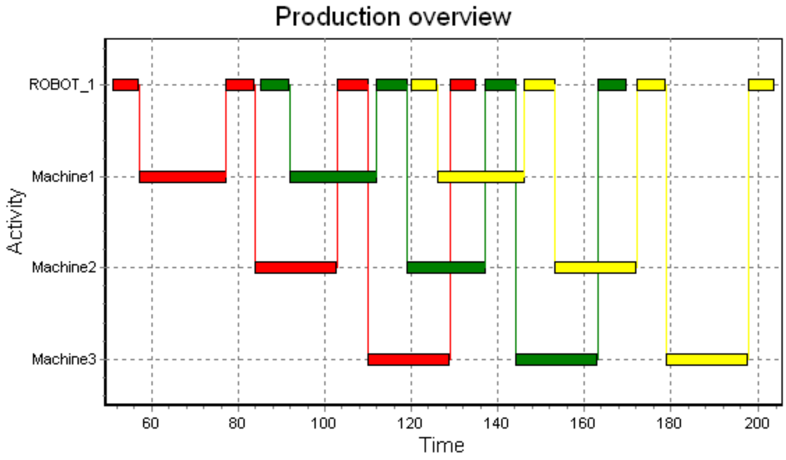

Fig. 8. Gantt chart fragment

On this basis it can be concluded that the simulation model works as designed. Then another simulation experiments were performed and the impact of changes of selected parameters on the system work was analysed.

For the given parameters of technological process, the impact of the maximum speed of the robot on the robot performance and the productivity of the system was examined. New generations of industrial robots are achieving increasing movement speed. The question is whether the use of newer robot will increase system performance?

In the simulation the movement speed of the robot was changed in the range from 15 to 180deg/s every 15 degrees. Initially strong impact of robot speed on the growth performance of the system can be noticed (Fig. 9). For ω_r = 180deg/s the productivity of 113 parts/hour was obtained. However, above the speed of about 90deg/s increase of productivity is very little. Increasing the speed of the robot by 100% (from 90 to 180) causes an increase in productivity, only by 8% (113/104 · 100%).

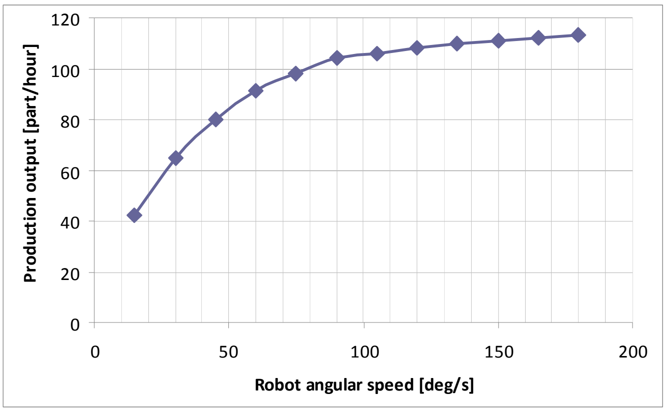

Fig. 9. Robot speed influence on the system productivity

The impact of variability of machine time on the formation of bottleneck was also analysed. Usually for technological reasons and a different scope of machine work operation times for various products are different. Deviations of those times lead to the formation of bottlenecks that result in reducing the production flow and thereby influence the productivity of the system. But removing one bottleneck causes a new bottleneck appearance elsewhere. In an experiment prolonged time of one operation of product Δt at various stages of the system was assumed. Input data can be represented in matrix t_{ij}, where i is the product number and j is the number of machine.

$$t_{ij} = \begin{matrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \end{matrix} \tag{10}$$

How this time delay affects system performance was observed during simulation and some results are presented in table 2.

Tab. 2. System productivity with bottleneck effect

Nr	**Product**	**Machine time delay Δt_{ij} (base time=17s)**			**Productivity [parts/hour]**
		M1	**M2**	**M3**	
1	**1**	0	0	+1	103
	2	+1	0	0	
2	**1**	0	+1	0	101
	2	0	+1	0	
3	**1**	+2	0	0	100
	2	0	0	+2	
4	**1**	0	+2	0	98
	2	0	+2	0	
5	**1**	+3	0	0	100
	2	0	0	+3	
6	**1**	0	+3	0	96
	2	0	+3	0	
7	**1**	+5	0	0	97
	2	0	0	+5	
8	**1**	0	+5	0	91
	2	0	+5	0	
9	**1**	0	0	+5	92
	2	0	0	+5	
10	**1**	+5	0	0	93
	2	+5	0	0	

The analysis shows that even minimal latency has significant impact on system performance. The most disadvantageous situation is the accumulation of long operation on the same stage of the production process, because it causes the greatest decreasing of system productivity. However, if extended times appear on different machines, their influence is weaker and system can achieve higher productivity. Certain configuration of the operation times gives slightly better results from other very similar data. This may be due to the accumulation of minor delays and date rounding, what causes that each case should be carefully examined. Because the robot work cycle is resistant to disturbances, the system can work even with greater disturbances but that will cause lower productivity.

5. CONCLUSIONS

Industrial robots are widely used in the different industries because they have many advantages. However, the design of robotic system is very complex and demands a thorough analysis of many factors that affect the system operation. Efficient use of robots requires a thorough analysis of robot movements. Planning of robot work cycle is needed, to specify the conditions for the productivity of the manufacturing system. Analytical solution of this problem is difficult, but assist of computer software and various simulation tools can greatly facilitate this task. Analysis of the simulation model reflects if the preliminary draft cooperates with the production system. The greatest advantage of simulation is that simple simulation models can be easily improved with additional elements. Simulation allows a broad analysis of the robot work and allows checking robot activity in different production conditions. This analysis can be used as a basis for designing the detailed configuration of the robotic cell, including the arrangement of workstations and the development of robot control program. Results from simulation can be also used for the economic analysis of profitability of robot use. Because robotic applications is difficult, this can be corresponding solutions to overcome some production problems, for providing enterprises some useful advices to prevent the appearance of unexpected bottlenecks, or to reduce the unexpected production fluctuation.

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