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A Lean Robotics Approach to the Scheduling of Robotic Adhesive Dispensing Process

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ABSTRACT

Modern implementations of industrial robots require the use of extensive knowledge and novel concepts. To bring real benefits, robotized processes must be analysed in detail. One can now observe an increasing use of lean robotics, a concept that is primarily intended to simplify processes and eliminate inefficient activities. This paper deals with industrial robot task scheduling in the adhesive dispensing process. The first part of the paper presents the modern concept of production process robotisation and reviews the literature on industrial robot task scheduling. After that, the problem of robotic adhesive dispensing on the electronic components of a printed circuit board (PCB) is presented. Another section of the paper describes the scheduling of effective and supporting tasks of the robot in the analysed process with the use of alternative dispatching rules. The determination of a schedule that is optimal in terms of the defined objective made it possible to discuss the results and reach valid conclusions. The study has confirmed that modern concepts are useful for simplifying robotic production processes.

Keywords: industrial robot, adhesive dispensing, robotic task scheduling, lean robotics.

INTRODUCTION

One of the contemporary measures of the development of production systems is an increasingly widespread use of industrial robots [1]. The increase in robot implementation is mainly due to the benefits their use brings, such as increased efficiency and flexibility of production, increased safety, high-quality production, increased reliability, and reduced production costs [2, 3].

The range of applications for robots in production processes is very wide these days. Besides standard transport operations, robots are more and more widely used in precision operations such as welding, painting and adhesive/glue dispensing [4, 5, 6].

Regardless of the robot use, task type and robotic cell complexity, robotic processes must be analysed in detail. Practice shows that the perception of robotization depends on the time after robot implementation (Fig. 1). Immediately after the decision of robot implementation there is enthusiasm resulting from the robotization of a given process; it is followed by a phase of problems, the solution of which ultimately leads to the adaptation of a fully operational robotic cell [7].

Robotic implementations should therefore be achieved with the use of extensive knowledge and modern concepts, not to mention that they should be preceded by appropriate analyses. A growing trend is to use lean robotics, a concept that recommends in-depth analysis and thus significant simplification of the production process, so that the use of a robot would bring as many benefits as possible.

LEAN ROBOTICS

Lean Robotics (LR) is largely derived from the well-known and more and more widely used concept of Lean Production or Lean Manufacturing [8]. The main aim of the LR concept is to develop robotic solutions of the lowest possible

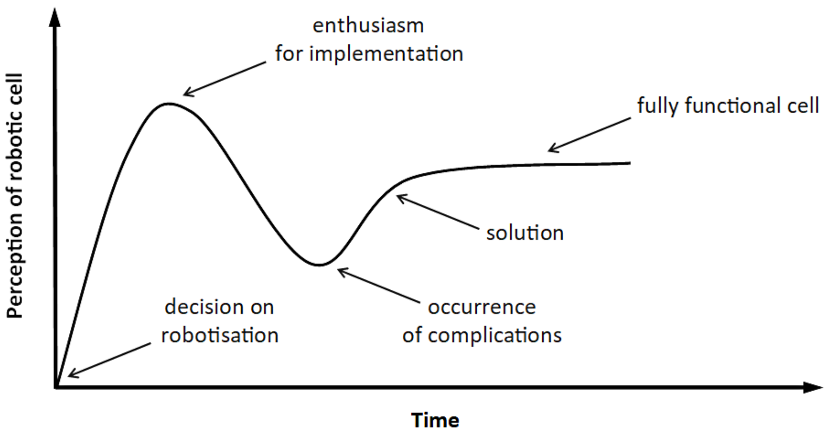

Fig. 1. Perception of robotisation [7]

complexity, which leads to many other benefits such as reduced complexity and – consequently – lower costs and a higher return on investment (ROI) (Fig. 2). The essence of LR is thus to maximize the usefulness for the client while minimizing waste [9].

LR is therefore a modern approach to the robotisation of production, wherein the production process is carefully considered and analysed. As a result, all ineffective actions are eliminated, and the ”client” (i.e. successive workstations) receives the highest possible surplus value – the effect of robot implementation in a given process [7]. This approach makes it also possible to mitigate effects of the complication phase, and hence to organize more efficiently a fully functional workstation.

One of the main causes of ineffective use of industrial robots is inadequate industrial robot task scheduling and path planning [10, 11]. Even a small change in task order affects both a given robotic process and the overall production process [4]. Therefore, robotic tasks scheduling is one of the key aspects in the LR approach.

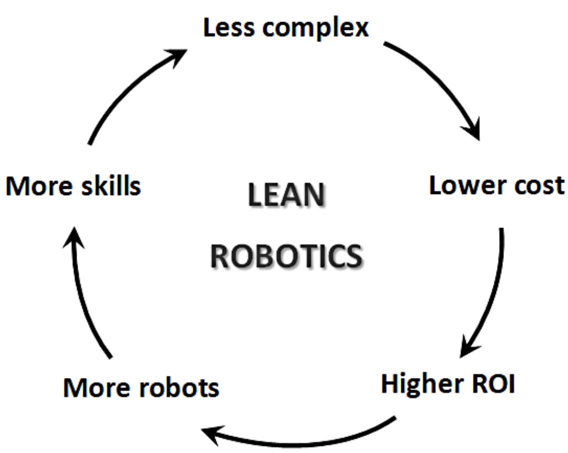

Fig. 2. Main assumptions of Lean Robotics [7]

ROBOTIC TASK SCHEDULING

Optimal robot task scheduling results in real improvement of implemented processes [2]. In practice, however, this problem is usually belittled, and robot programming is only based on the integrator’s experience and intuition.

Industrial robot task scheduling consists of:
- production scheduling, where the creation of an overall schedule and the proper planning of all production tasks are analysed, with a special focus on robotic cells [12, 13, 14],
- task-level planning, where the scheduling of specified tasks performed by the robot is analysed, with a focus on strictly specified processes [6, 15, 16].

The problem of production and production process scheduling has been investigated in numerous studies. In these studies, scheduling processes are analysed by classifying scheduling problems depending on: production system type [17], randomness [18], process dynamics and change over time [19], practice-related aspects [20]. The literature review shows that there also exist studies that focus on industrial robot scheduling. These studies usually investigate several of the above-mentioned scheduling problems, and the effect of robot implementation is analysed in terms of its effect on the overall production process [12, 15, 21], robot task scheduling in specified jobs [16, 22], and precise determination of robot end effector trajectory [6, 23]. It should also be mentioned that the number of studies devoted to the above problems is on the increase. As a result, these issues have become very topical and the need for conducting research in this area have become of significant importance.

Previous studies on production scheduling seek to extend classical scheduling problems to include issues related to robot use. The majority of these studies focus on the use of robots in handling processes [13], and problems of this type are usually solved with the use of well-known scheduling methods. Shabnay and Arviv [12] investigated the use of a robot for transporting elements between two workstations and its effect on the defined objective, i.e. makespan. Gultekin et al. [14] investigated a flow-shop scheduling problem where the robot was operating several machines moving on a running track. Zacharia et al. [15] and King et al. [13] stressed that robotised environments were strongly dynamic, and hence the formulated problems were characterized by significant computational complexity. Śmigiel et al. [24] and Zanlongo [25] investigated the problem of multi-robot task scheduling in terms of cooperation between the robots and detailed analysis of their path trajectory.

As far as task scheduling in specific production processes is concerned, previous studies usually provide in-depth analyses of robot movement parameters while neglecting the important aspect of robot task scheduling. Tereshchuk et al. [21] proposed that the robot path planning problem should be described by means of the classic traveling salesman problem (TSP). This type of approach was adopted in numerous studies. For example, Baizid et al. [16] proposed the use of a genetic algorithm to solve this problem. Ericsson and Nylén [26] proposed a solution in which detailed process parameters were taken into account. Mohsin et al. [6] proposed a solution in which path planning was combined with simultaneous force control in a robotic grinding process. It was also observed that robot path planning problems were solved by multi-criteria analysis, wherein the solutions consist of determining relationships between path shortening, cost minimization, collision elimination and failure rate reduction [27, 28].

The literature review shows that previous studies focused either on entire production scheduling or on precise path planning combined with in-depth analysis of parameters. Consequently, there a distinct lack of solutions that would stress the significance of industrial robot task scheduling in specific processes. This aspect is of utmost importance in the LR approach, not to mention the fact that there exist only very few studies devoted to the LR concept [9, 29]. It is therefore necessary to conduct research involving detailed analyses of task scheduling at a level of specific technological operations. Robot task scheduling should be done considering the nature of robot elementary movements. Every problems requires an individual approach and analysis.

In response to the above problems, this study considers the problem of task scheduling in robotized adhesive dispensing. It is worth mentioning that problems of this type have been quite seldom investigated in previous studies [30, 31, 32] and that the approach employed in this work is an alternative to the methods reported in the literature.

ROBOTIC DISPENSING SCHEDULING PROBLEM

The industrial robot task scheduling problem analysed in this study relates to robotic adhesive dispensing on electronic components of a printed circuit board (PCB). Solutions of this type are more and more widely used as an alternative to standard techniques for combining parts [33, 34]. Fig. 3 shows an example of an electronic circuit for which robotic adhesive dispensing on components 1–5 is performed.

The analysed system has the dimensions of are 1000 × 650 mm, while the dimensions of key components are given in Table 1.

This problem must be analysed in terms of robot movements [36]:

- effective movements when the robot performs the target task, i.e. adhesive dispensing,

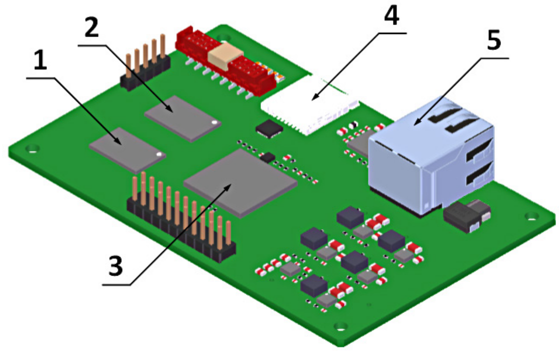

Fig. 3. PCB in the analysed adhesive dispensing process [35]

Table 1. Dimensions of assembled components

Component	Dimensions [mm]
PCB	1000.00 × 650.00
1	14.00 × 9.00
2	14.00 × 9.00
3	17.00 × 17.00
4	13.85 × 15.95
5	15.88 × 21.48

- supporting movements when the robot performs successive effective tasks, i.e. dispensing the adhesive on successive components.

Examples of these movements are shown in Fig. 4.

For the analysed process to be implemented, the following assumptions must be met:

1. The adhesive is dispensed on every component continuously along the entire contour, and the start point of adhesive dispensing on a given component is the end point at the same time.
2. As for components 4 and 5 the adhesive is only dispensed on the key lines between the PCB and the components while maintaining the adhesive dispensing continuous.
3. Supporting movements of the robot are performed observing the end effector safe movement condition (preventing collision by ensuring an appropriate distance of the robot from the PCB surface).

To analyse and plan rational scheduling of adhesive dispensing on electronic components, this problem should be considered as a case of robotic task scheduling in terms of the defined objective.

SCHEDULING TASKS IN THE ROBOTIC DISPENSING PROCESS

Objective

The objective of the study was to find optimal job scheduling in terms of achieving the objective, i.e. minimizing the makespan of PCB assembly (C_{max} indicator).

Mathematical model of the analysed problem

The analysed problem should therefore be defined as the scheduling of tasks on a single machine in an open-shop environment. This is because open-shop scheduling is characterized by a lack of a specific order of jobs, which is very common during the execution of jobs in the electronics or computer industries [37]. In the robotic adhesive dispensing scheduling process under study, individual jobs consist of making connections of a given element, which will combine appropriate auxiliary and effective movements of the robot.

Robot task scheduling in the analysed adhesive dispensing process can therefore be described by the following sets:

- a set J defining the number of jobs:

$$J = \{J_1, \dots, J_i, \dots, J_n\};\ i \in \langle 1; n \rangle;\ n = 5 \quad (1)$$

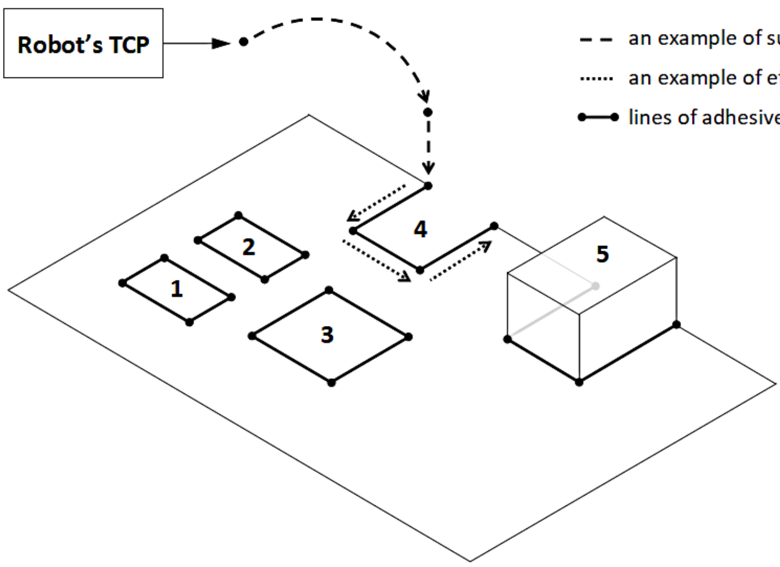

Fig. 4. Types of movements performed by an industrial robot in the adhesive dispensing process under analysis

- a set M defining the number of machines:

$$M = \{M_j\};\ j = 1 \tag{2}$$

The execution of a job J_i on a given machine M_j shall be called an operation, which means the following can also be defined:

- a set O defining the operation order:

$$O = \{o_1, \dots, o_k, \dots, o_n\}; k \in \langle 1; n \rangle; n = 5 \tag{3}$$

where: $o_k \in \langle 1; n \rangle$ – the number describing the order of the *k*-th job.

- a set PT describing the processing times:

$$PT = \{pt_1, \dots, pt_l, \dots, pt_n\}; l \in \langle 1; n \rangle; \\ n = 5 \tag{4}$$

where: pt_l – the processing time of the *i*-th movement of the robot, that is:

$$pt_l = pts_l + pte_l \tag{5}$$

where: pts_l – the processing time of supporting movement in the *l*-th operation,
pte_l – the processing time of effective movement in the *l*-th operation.

The objective function will thus be expressed by the following relationship:

$$\min C_{max} = \\ = \min \sum (pts_l + pte_l); l \in \langle 1; n \rangle; \\ n = 5 \tag{6}$$

It should be mentioned that due to its high degree of computational complexity, the analysed robot task scheduling problem belongs to a class of NP-hard problems. In effect, it is only possible to find an approximate solution. Taking the above into consideration, this study proposes that task scheduling be made using a selection of dispatching rules. This approach allows for quick solution, analyses of alternative scenarios, and easy implementation [38]. This approach made it possible to design alternative robot task schedules and to determine a schedule that was optimal in terms of the defined objective.

Description of the proposed solution

Due to a high complexity of the analysed robotic adhesive dispensing scheduling problem, dispatching rules were used as a task scheduling tool. The dispatching rule can be defined as [39]:

$$P_{IJ}(t) = \min\{z_{ij}(t)\}, (i, j) \in A(t) \tag{7}$$

where: $P_{IJ}(t)$ – the priority of the *J*-th operation of the *I*-th job in time *t*;
$z_{ij}(t)$ – the priority index of operation *j* of job *I* in time *t*,
$A(t)$ – the set of operations to be performed in time *t*.

Given a lack of data about the processing times of individual operations in the analysed case, priorities were assigned to individual jobs depending on the distance of the electronic components from the defined base point. Practice shows that with constant robot speed, auxiliary movements greatly depend on the distance between the points relating to effective movements.

Priority indicator values for individual jobs were determined with the use of the scheme of robot end effector trajectory points arrangement shown in Fig. 5.

Based on the above assumptions, the following dispatching rules were employed in scheduling:

- a dispatching rule for a job where the central point C_i is located the closest to the x axis of the coordinate system (*NXA*);
- a dispatching rule for a job where the central point C_i is located the closest to the y axis of the coordinate system (*NYA*);
- a dispatching rule for a job where the central point C_i is located the closest to the point P denoting the origin of the coordinate system (*NXYP*);
- a dispatching rule for a job where the central point C_i is located the closest to the point CP denoting the point of intersection of the symmetry axes of the PCB (*NCP*);
- a dispatching rule for a random job (*RAND*).

The use of appropriate dispatching rules made it possible to determine the values of elements in the set O, plan robot paths, and conduct simulations to analyse the robotic dispensing process under study.

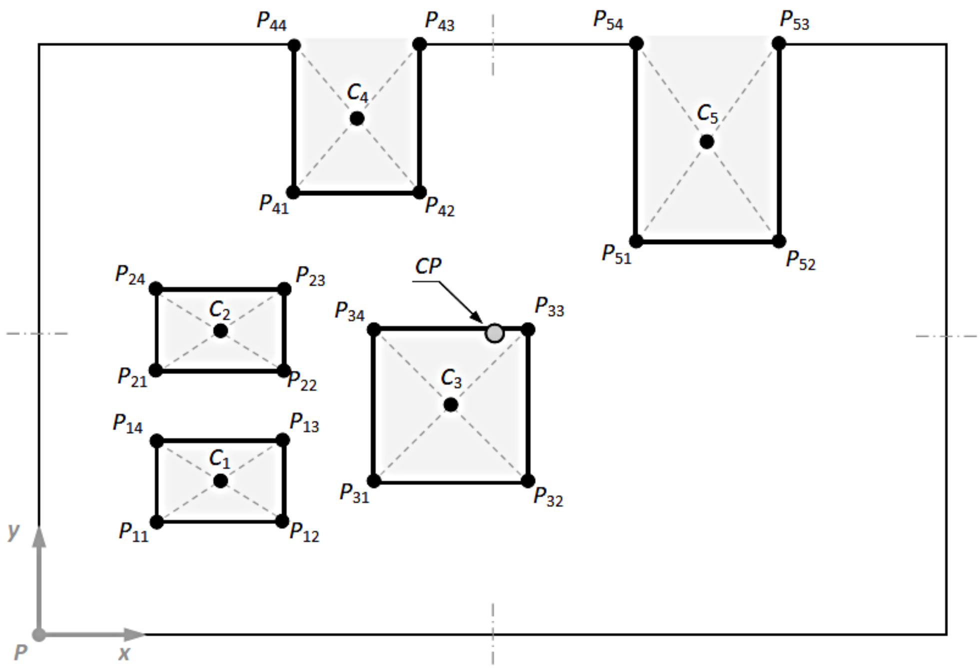

Fig. 5. Characteristic points of robot end effector trajectory

ROBOTIC DISPENSING PROCESS ANALYSIS

Obtained task orders

To implement the dispatching rules in the Matlab software, a script was developed for determining the coordinates of C_i points based on the defined dimensions of the PCB, as well as on the dimensions and coordinates defining the position of electronic components. The determined coordinates made it possible to determine distances that were of key importance from the point of view of the applied rules. To that end, the built-in function of calculating the Euclidean norm was employed (*norm*). Obtained results were then used for job scheduling according to the adopted dispatching rules, using the *sortrows* function for sorting data in a table. On the other hand, the *randperm* function, which returns a random permutation from a given set of data, was employed for the random dispatching rule.

Table 2. Order of robot trajectory points for individual dispatching rules

Dispatching rule:	Values of set *O*	Determined order of points *
NXA	{1,3,2,5,4}	$P_{12}-P_{13}-P_{14}-P_{11}-P_{12}-P_{31}-P_{32}-P_{33}-P_{34}-P_{31}-P_{22}-P_{23}$ $-P_{24}-P_{21}-P_{22}-P_{54}-P_{51}-P_{52}-P_{53}-P_{43}-P_{42}-P_{41}-P_{44}$
NYA	{1,2,4,3,5}	$P_{14}-P_{13}-P_{12}-P_{11}-P_{14}-P_{21}-P_{24}-P_{23}-P_{22}-P_{21}-P_{44}-P_{41}$ $-P_{42}-P_{43}-P_{34}-P_{31}-P_{32}-P_{33}-P_{34}-P_{54}-P_{51}-P_{52}-P_{53}$
NXYP	{1,2,3,4,5}	$P_{14}-P_{13}-P_{12}-P_{11}-P_{14}-P_{21}-P_{24}-P_{23}-P_{22}-P_{21}-P_{34}-P_{33}$ $-P_{32}-P_{31}-P_{34}-P_{43}-P_{42}-P_{41}-P_{44}-P_{54}-P_{51}-P_{52}-P_{53}$
NCP	{3,4,2,5,1}	$P_{34}-P_{33}-P_{32}-P_{31}-P_{34}-P_{43}-P_{42}-P_{41}-P_{44}-P_{23}-P_{22}-P_{21}$ $-P_{24}-P_{23}-P_{54}-P_{51}-P_{52}-P_{53}-P_{13}-P_{14}-P_{11}-P_{12}-P_{13}$
RAND1	{5,3,4,2,1}	$P_{53}-P_{52}-P_{51}-P_{54}-P_{33}-P_{32}-P_{31}-P_{34}-P_{33}-P_{43}-P_{42}-P_{41}$ $-P_{44}-P_{23}-P_{22}-P_{21}-P_{24}-P_{23}-P_{13}-P_{12}-P_{11}-P_{14}-P_{13}$
RAND2	{2,4,5,3,1}	$P_{23}-P_{24}-P_{21}-P_{22}-P_{23}-P_{44}-P_{41}-P_{42}-P_{43}-P_{54}-P_{51}-P_{52}$ $-P_{53}-P_{33}-P_{34}-P_{31}-P_{32}-P_{33}-P_{13}-P_{14}-P_{11}-P_{12}-P_{13}$
RAND3	{5,4,1,3,2}	$P_{53}-P_{52}-P_{51}-P_{54}-P_{43}-P_{42}-P_{41}-P_{44}-P_{13}-P_{12}-P_{11}-P_{14}$ $-P_{13}-P_{31}-P_{32}-P_{33}-P_{34}-P_{31}-P_{22}-P_{21}-P_{24}-P_{23}-P_{22}$

Note: *points in bold denote the start and end of parts assembly process.

When determining the order of robot trajectory points, it was assumed that the first point of the first job would be selected in such a way that the end point was as close as possible to the start point of a successive job. Hence, successive jobs would start from the points located the closest to the end point of a previous job. In addition to that, the direction of robot movements was set in such a way that the trajectory did not have to be changed in an abrupt manner. Obtained orders of points are listed in Table 2.

The determination of the order of points made it possible to perform analyses aimed at finding the optimal job schedule.

Analysis of task execution by the robot

To investigate alternative robot task schedules, a model of workstation for the analysed adhesive dispensing process was designed using the K-ROSET simulation software (Fig. 6). The workstation consisted of the RS003N industrial robot provided with an adhesive dispensing head, a robot base, and a work table with a simplified 3D model of the analysed PCB.

After that, key points of the robot path were defined using the afore-mentioned simulation software, and robot programs were developed considering the designated order of points. For this purpose, robot control codes were programmed using the AS language (Table 3). Commands were selected in such a way that the process was implemented in compliance with real production conditions. The robot's operating parameters were defined, such as speed, interpolation of movements, and the accuracy of moving from one point to another. While programming the robot (based on verification tests), focus was put on proper reorientation of the robot tool and prevention of collisions with the PCB and its components.

The designed workstation model made it possible to simulate the robot's movements in accordance with the order of points defined for every dispatching rule. Simulations provided detailed information about the times of elementary movements of the robot, effective and auxiliary alike. The use of a built-in cycle time tool provided detailed reports about the times of constituent movements of the robot (Table 3).

The simulations of alternative robot task schedules made it possible to analyse obtained results and formulate conclusions.

DISCUSSION

The simulation results were used to compare the times of auxiliary and effective robot movements for each of the obtained task schedules (Tab. 4). An analysis of the data demonstrates that the optimal job schedule in terms of the defined objective was obtained with the *NXYP* rule which prioritised the job whose central point C_i was located the closest to the origin of the coordinate system. The adopted objective criterion was $C_{max} = 135.71$ [s]. The least favourable task schedule was obtained with the random dispatching rule (RAND3).

The results show that the objective primarily depends on the time of supporting movements. The data in Figure 7 confirm that the times of effective movements (adhesive dispensing) are similar for every dispatching rule whereas the

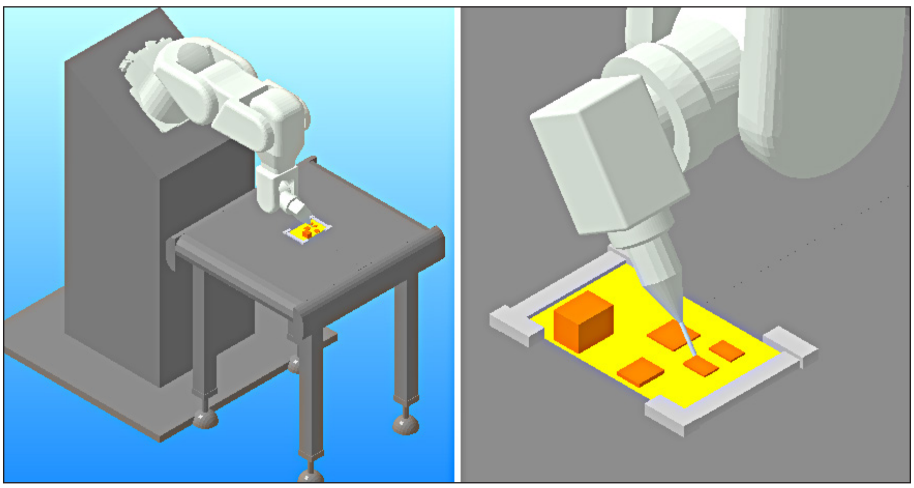

Fig. 6. Workstation for conducting simulations

Table 3. Selected results of robot movement simulations – the order of points according to RAND2

No.	Program	Step No.	Step	Moving time	Integration time
1	RAND2()	0001	SPEED 5	0.00	0.00
2		0002	JMOVE #CP	0.00	0.00
3		0003	JAPPRO #p23,30	4.71	4.71
4		0004	LMOVE #p23	2.34	7.05
5		0006	LMOVE #p24	7.52	14.57
6		0008	LMOVE #p21	1.73	16.30
7		0010	LMOVE #p22	7.49	23.79
8		0012	LMOVE #p23	1.63	25.42
9		0014	JAPPRO #p23,30	2.46	27.88
10		0015	JAPPRO #p44,30	7.23	35.11
11		0016	LMOVE #p44	2.27	37.39
12		0018	LMOVE #p41	2.24	39.63
13		0020	LMOVE #p42	7.68	47.31
14		0022	LMOVE #p43	2.11	49.42
15		0024	JAPPRO #p43,30	2.50	51.91
16		0025	JAPPRO #p54,30	7.26	59.18
17		0026	LMOVE #p54	2.34	61.51
18		0028	LMOVE #p51	7.30	68.81
19		0030	LMOVE #p52	8.16	76.97
20		0032	LMOVE #p53	5.92	82.89
21		0034	JAPPRO #p53,30	2.50	85.39
22		0035	JAPPRO #p33,30	4.22	89.61
23		0036	LMOVE #p33	2.37	91.98
24		0038	LMOVE #p34	7.36	99.34
25		0040	LMOVE #p31	2.14	101.48
26		0042	LMOVE #p32	7.39	108.87
27		0044	LMOVE #p33	2.24	111.11
28		0046	JAPPRO #p33,30	2.43	113.55
29		0047	JAPPRO #p13,30	3.74	117.29
30		0048	LMOVE #p13	2.37	119.66
31		0050	LMOVE #p14	7.46	127.11
32		0052	LMOVE #p11	2.69	129.81
33		0054	LMOVE #p12	7.49	137.29
34		0056	LMOVE #p13	2.75	140.05
Total					140.05

Table 4. Robotic adhesive dispensing times

Dispatching rule	Time [s]												
	Job J_1J_1		Job J_2J_2		Job J_3J_3		Job J_4J_4		Job J_5J_5		$\sum pts$	$\sum pte$	C_{max}
	pts_1	pte_1	pts_2	pte_2	pts_3	pte_3	pts_4	pte_4	pts_5	pte_5			
NXA	7.07	20.38	11.62	19.1	11.65	18.37	11.81	21.38	7.30	12.05	49.45	91.28	140.73
NYA	7.51	20.38	6.18	18.34	8.03	12.00	11.94	19.1	10.82	21.41	44.48	91.23	135.71
NXYP	7.51	20.38	6.18	18.34	11.23	19.14	11.84	12.03	7.23	21.39	43.99	91.28	135.27
NCP	7.06	19.10	11.87	12.03	12.06	18.37	11.81	21.38	7.78	20.40	50.58	91.28	141.86
RAND1	7.64	21.38	11.87	19.1	8.29	12.00	12.10	18.34	6.69	20.38	46.59	91.20	137.79
RAND2	7.05	18.37	11.97	12.03	12.1	21.38	9.09	19.14	8.54	20.38	48.75	91.30	140.05
RAND3	7.64	21.38	12.13	12.03	12.1	20.35	11.65	19.14	11.62	18.39	55.14	91.29	146.43

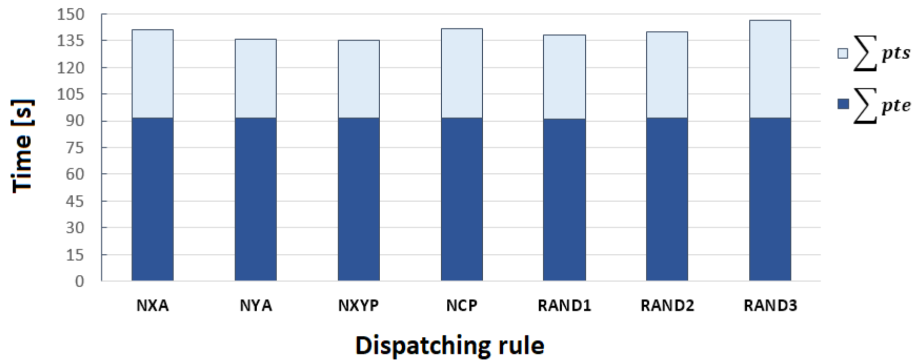

Fig. 7. C_{max} values obtained for the analysed dispatching rules

supporting movement times are variable and heavily dependent on the part assembly order.

The results also demonstrate that correct industrial robot task scheduling is of vital importance and that the assumptions of the Lean Robotics approach were valid. An analysis of the optimal and least favourable job scheduling results demonstrates that the difference between the objective criterion values is:

$$\Delta C_{max} = 146.43 - 135.27 = 11.16 \text{ [s]}.$$

Incorrect industrial robot task scheduling may therefore result in extending the schedule by as much as 7.62% per one PCB (Fig. 8). If the production process was implemented on a larger scale, this difference would cause real losses. For 10 PCBs the waste of time would be 111.6 [s], while for 100 PCBs – 1116 [s], which is enough for assembling parts on 8 additional PCBs.

The results confirm that robot task scheduling is a key to effective production robotisation. It is worth mentioning that the obtained robot task schedule is nothing but a suboptimal solution. Therefore, attempts should be made to investigate this process more comprehensively by modifying selected robot movement parameters and examining in detail robot end effector trajectories. Results of such analyses would probably allow for additional time savings, which – in turn – would bring real benefits to the entire production process. The selected PCB model state an example for analysis of the problem. Robotic adhesive dispensing process for other types and sizes of boards require carrying out separate studies. However, the process analysis methodology presented in this paper can be fully applied to it.

CONCLUSIONS

The use of industrial robots in different production processes is becoming more and more widespread. However, mere robot implementation is not enough these days because robotised processes require extensive knowledge and comprehensive analyses. Modern concepts such as Lean Robotics may be useful in this respect, as their use makes it possible to both eliminate ineffective activities and ensure efficient robot implementation in a given process.

This paper presents an analysis of robotic adhesive dispensing scheduling with the use of

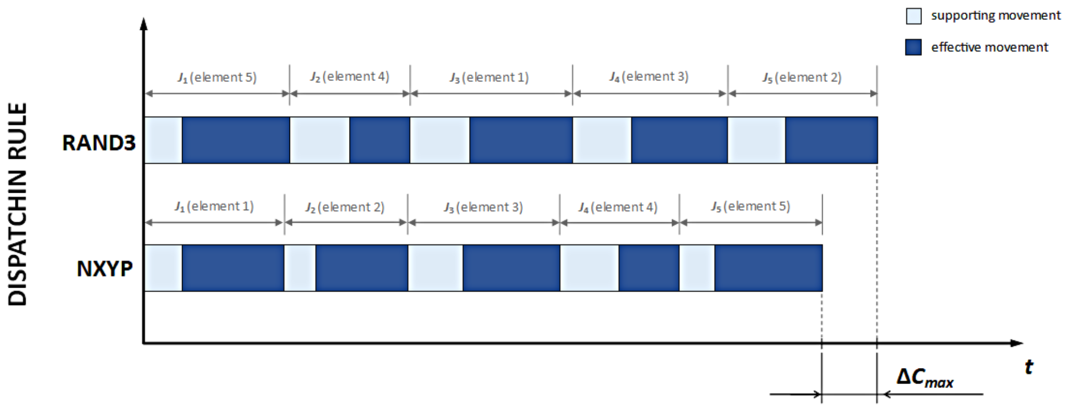

Fig. 8. Robotic adhesive dispensing scheduling – a comparison of extreme schedules

selected dispatching rules. Defining the problem as the scheduling of tasks on a single machine in an open-shop environment allowed to determined alternative schedules of robot work and selected the most advantageous work schedule, assuming as the criterion of the goal the time of completion. The important role of the makespan of the time of robotic operations, which can affect the entire production process, was also emphasized. Moreover, the results showed that the objective primarily depends on the time of supporting movements. This proves that further research will include process analysis for their reduction.

The study has shown that industrial robot task analyses and scheduling are of significant importance. Optimal robot task scheduling can bring many advantages, both for a given production process and for production as a whole. The research described in this paper should be continued and focus on issues such as: makespan prediction based on individual processing times of elementary robot movements; task scheduling optimization via analysis and modification of selected robot movement parameters; and alternative arrangements of elements on the workstation.

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