Article

Scheduling the Process of Robot Welding of Thin-Walled Steel Sheet Structures under Constraint

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Abstract: Industrial robot work optimization has been extensively studied. The main reason for analysis is the growing number of robots implemented in the different manufacturing processes. In order to benefit from the implementation of industrial robots, each implementation process ought to be preceded by an in-depth analysis of the stand work. Often the integrator's intuition is the only base for decisions. This work focuses on the need for individualized scheduling and analysis of robotic production tasks in the context of overall production scheduling. The method of alternative schedules analysis was presented. The paper presents a scheduling process for an industrial robot in the process of robot welding of thin-walled steel sheet structures under constraints caused by the process technology. The proposed method allowed to reduce the assumed time criterion at the level of 5.4% for one detail. The obtained value of technological operation time reduction resulted in increased time savings throughout the entire production process.

Keywords: industrial robots; task scheduling; robotic welding

1. Introduction

1.1. Industrial Robots Utilization

The robotization of modern production processes has become ubiquitous. Lately, industrial robots are used not only in large corporations, but more and more often, they are employed for manufacturing processes in small and medium-sized enterprises [1,2]. The implementation of robots increases due to the benefits of their use, mainly an increase in productivity and flexibility of production, increased safety, high-quality production, more reliability, and reduced production costs [3,4].

Robots can be employed in a wide range of manufacturing processes. Apart from the typical transport-related work, robots are more and more frequently used for precision work such as welding, painting, or gluing [5,6]. As in the case of overall production processes, robotic processes require careful analysis to ensure efficiency and real benefits [7]. The effective use of production robots requires, in fact, the proper definition of the robot's work parameters, selection of the equipment used or programming of the robot's paths and work.

1.2. Robotic Tasks Scheduling

The appropriate planning of the work to be conducted by the robot allows for a substantial improvement of the real processes [3]. In the case of production practice, this problem is usually underestimated, and robots are programmed on the basis of the integrator's intuition. However, this issue is extremely important because it can be considered in numerous aspects. Industrial robot scheduling problems are usually analyzed in terms of [8,9]:

- Comprehensive production scheduling: In this case, mainly the proper scheduling of all production tasks with special emphasis on the workstations constituting a manufacturing cell is considered, and the goal criterion becomes the task execution time or manufacturing costs [10];

- Scheduling of specific tasks performed by robots: A strictly defined process is analyzed, taking into account aspects of the robot kinematics, process requirements, or the collisions between the robot and the elements of the workstations constituting a manufacturing cell [5].

The above-presented problems are usually discussed separately in the literature. Production scheduling with robotic workstations is then referred to as "Production Scheduling", while scheduling of lower-level work as "Task-Level Planning" [8]. Adopting a rigid division, however, is a rather significant simplification of the problem. Detailed planning of a robotic process significantly influences the whole production process. For example, increasing or decreasing the time of a robotic operation will affect the total production time [11]. In addition, there is a need for an individual approach to each process supported by industrial robots since each is characterized by the occurrence of many, often individual constraints [12]. The key aspect becomes the need to consider and to define their impact.

This paper focuses on the need for individualized scheduling and analysis of robotic production tasks in the context of overall production scheduling. Each process requires individual analysis and optimization, as well as taking into account the numerous constraints [13]. This paper presents an example of a robotic welding process analysis of a sheet metal structure using the classical theory of constraint scheduling.

In Section 2, typical approaches to the problem of scheduling robotic production cells, robot path planning, and robotic welding proposed in the literature are presented. Section 3 presents the description and assumptions of the problem of selecting the most advantageous welding robot path in the joining process of a thin-walled sheet metal structure. Section 4 describes the proposed solution using elements of constrained serial task theory. An analysis of the process with special emphasis placed on possible work scenarios, analyses the times of individual robot movements and discusses the results obtained. The paper is concluded with a sub-summary and plans for further research.

1.3. Existing Work Discussion

Scheduling of production and related processes was researched in many works. The authors analyze the processes of scheduling, dividing the problems occurring in it into: types of production systems [14], the occurrence of the phenomenon of randomness [15], the dynamics of processes and changes in time [11], or their relation to practice [1]. Task scheduling problems are considered in various production environments. The flowshop [16], job-shop [17] and open-shop environments [18] are the most frequently analyzed in the literature. Due to the fact that the robotization of various production processes often involves several of these areas simultaneously—in the literature, one can clearly distinguish the area of task scheduling in which industrial robots are used. Then, the implementation of robots is analyzed in terms of their impact on the overall processes [9,10,19], serialization of robot tasks for specific jobs [20,21], or precise determination of robot paths [5,22]. Upon analyzing the literature in the above-mentioned areas, it can be observed that the number of publications in recent years increased significantly. This proves the relevance of the issues raised, as well as the timeliness of research in this area.

In the area of works on production scheduling, the authors try to supply the classical problems with issues related to the use of robots. In the research related to the field of production scheduling, attention is paid to the use of robots in processes of the handling type [23], and well-known scheduling methods, such as the Branch and Bound method, are used to solve such problems. For example, in [10], a robot is used for transporting elements between two production stations, and the authors analyze its impact on the schedule, with the target criterion being the execution time of all orders. In turn, the work [24] considers a flexible flow-shop class system, in which the robot has the task of handling three technological machines moving along a running track. Many papers in this area also emphasize that robotic environments are highly dynamic, and thus the formulated problems are characterized by considerable computational complexity [9,23]. Sometimes

the problem of scheduling with several robots is discussed [25,26], but this issue more often concerns cooperation between robots or a detailed analysis of robot paths.

In the case of work serialization in specific production processes, the authors usually place focus on thorough analyses of robot paths while omitting the important aspect of robot task serialization. Various processes are described using the classical Travelling-Salesman Problem (TSP) [19,20], and numerous algorithms are used to solve the problem. Gene-type algorithms are most often applied [9,20]. The authors propose solutions with detailed process parameters considered [27]. For example, in [20] the authors address the issue of shortening the transition paths by analyzing the coordinates of the trajectories. In turn [5], they present a solution aiming at appropriate path planning with simultaneous force control in the process of robotic grinding. The works very often deal with the aspect of the occurrence of collisions between the elements of the infrastructure of robotic workstations [9], with the target criterion usually being the execution time of the robot tasks [10]. Approaches based on artificial intelligence are increasingly proposed in the literature also [28,29]. The utilization of AI techniques provides control process automation and simplification [30,31]. Moreover, the mentioned solutions are applicable in the whole production systems analysis [32].

The problems of planning robot paths are subjected to multi-criteria analysis. The relations between shortening paths, minimizing costs, excluding collisions and reducing the failure rate of robots are sought as solutions [17,33,34].

The literature analysis showed that solutions having the character of a "smooth transition" between the topics of production scheduling and the topics of robot path planning are very rarely addressed in the literature [35]. Most works focus either on scheduling overall production processes or on precise path planning along with thorough parameter analysis. The majority of robot task scheduling work deals with issues in the use of mobile robots [36–38].

In the field of robotic welding, which is the topic of this paper, the authors focus on in-depth analyses of the process itself. The following issues are addressed: the selection of process parameters and the robot path supported by information systems [39], the use of additional hardware—e.g., a vision system [40], the use of genetic or memetic algorithms [41] or neural networks [42] for weld optimization analysis, or collision detection using ant algorithms [43]. Thus, in the works on robotic welding, issues are presented where the authors do not focus on the exact planning of the robot's work and the appropriate refinement of its tasks. The literature review did not find any works analyzing the welding process as a problem of scheduling robot tasks, considering the existing limitations of the process.

Therefore, the task scheduling processes ought to be further analyzed in relation to specific technological operations. In-depth planning of paths should be preceded by a serialization of robot tasks considering its elementary movement occurring in the process. In addition, the key aspect of the existence of numerous process limitations must be remembered—each problem requires an individual approach and analysis.

2. Problem of Robotic Welding under Constraint

The analyzed problem of planning the robot's path of passage concerns the process of robotized welding of a thin-walled sheet metal structure—a metal electrical box used to protect the switching station (Figure 1). The subject of a thin-walled structure is frequently analyzed in the literature [44]. The research mainly includes inter alia, strength analysis [45], stability assessment [46] and the very important aspect of structure joining [47,48].

Figure 1. Photos of the welded detail.

The considered detail is a product manufactured by the facility from the range of small and medium-sized enterprises. Robotized welding of metal boxes with overall dimensions of $500 \times 500 \times 190$ mm is subjected to analysis. The operations performed prior to robotized welding are the laser cutting of the box section and bending of the edges of the sidewalls and the flange on a press brake. The welding process is performed on a workstation equipped with a welding robot, as well as a turntable that allows one to perform all connections of the construction in two positions (two corners in each position).

In this case, the welding robot will perform two types of movements [8]:

- Effective movements (effective tasks)—during which the robot performs the target work—welding.
- Supporting movements (supporting tasks)—during which the robot moves between the effective tasks (between performing successive welds).

An additional aspect of the process is the assumptions resulting from the structure of the workpiece:

1. The box is placed on a turntable so that one of the walls is parallel to the base of the robot, and the operation is performed in two positions—in one position, the overall joints of the two corners are made (Figure 2).
2. In order to stiffen the structure, the wall joints must be manufactured first (section *AB* and *DE* in Figure 2), and the direction is arbitrary.
3. The flange connections are to be made last in the given position (sections *BC* and *EF* in Figure 2), and due to the possibility of corner burns, they must be made in the "top-down" direction—e.g., from point *C* to point *B*.
4. After completing the connections, the table with the part is rotated by 180° in order to make opposite connections in the second position.

The main limitation to this process is the sequence of the effective tasks and the supporting tasks of the welding robot (Figure 2).

In order to optimize the presented process of robotized welding of thin-walled structures, it is necessary to thoroughly analyze the process while taking into account the limitations mentioned above.

Due to the symmetrical nature of the structure, the problem can be limited to scheduling the robot to work in one position of the turntable. The most beneficial path of the robot in one position will allow it to be repeated during the execution of subsequent joints.
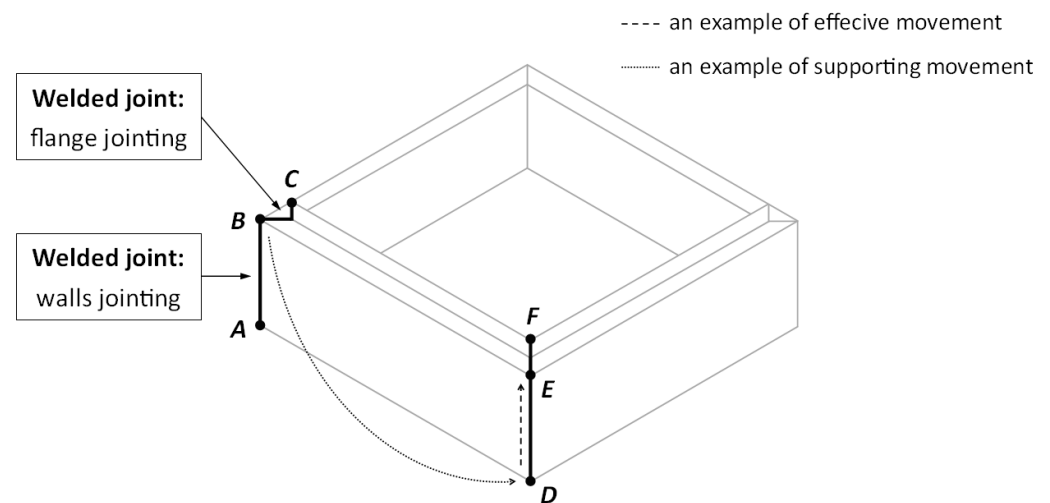
Figure 2. Joints in a single position.

3. Scheduling Tasks of a Welding Robot

3.1. Objectives

The aim of this work was to determine the most beneficial path of the welding robot in terms of the adopted criterion of the goal, i.e., the makespan of a technological operation in one position.

3.2. Mathematical Model of the Issue

The analyzed problem can be expressed using Graham's notation, which in the literature is also referred to as $\alpha \mid \beta \mid \gamma$ notation. Assuming the existing constraints of the process, as well as the adopted objective function, the problem will be described in the following manner:

$$1 \mid prec \mid C_{max} \tag{1}$$

where:

1—number of machines,
prec—precedence constraints,
C_{max}—makespan (objective criterion).

The analyzed problem can be defined as the scheduling of tasks on one machine where the individual tasks will be the corresponding effective and supporting movements of the welding robot in one position of the workpiece. In addition, there are precedence constraints in the scheduling process [49]. Therefore, the sequence of tasks (robot movements) is partly determined by the technological requirements of the process. For example, the joining of the structure's flange follows the joining of the walls, but they may be performed in an alternative order (the first to be performed may be the joining at section *CB* or *FE*). Consequently, there will be alternative realizations of auxiliary movements—for example: from point *D* to point *C* or to point *F* (Figure 2).

The problem of this type in the literature is included in the class of NP-difficult problems [50] characterized by a high degree of computational complexity, consequently a very high difficulty in finding an exact solution. This complexity increases along with the number of tasks considered in the scheduling process.

The problem of scheduling the movements of a welding robot ought to, therefore, be described by the following sets:

- Set *J* defining the number of tasks (robot movements):

$$J = \{J_1, \ldots, J_i, \ldots, J_n\}; \; i \in \langle 1; n \rangle; \; n = 7. \tag{2}$$

- Set M defining the number of machines:

$$M = \{M_j\}, \ j = 1. \tag{3}$$

The execution of a task J_i on a given machine M_j shall be called an operation, where for $i \in \{1, 3, 5, 7\}$ the operation will consist of an effective motion, while for $i \in \{2, 4, 6\}$ it will consist of the execution of a supporting motion. The key aspect becomes, therefore, the definition of the elements:

- Set O defining the order in which the robot effector is moved between each point:

$$O = \{o_1, \ldots, o_k, \ldots, o_n\}, \ o_k = XY, \ o_{k+1} = YZ, n = 7, \ k \in \langle 1; n \rangle, \tag{4}$$

where:

o_k—order in which the segment is travelled,
X, Y, Z—point designation.

- Set PT defining the times of individual operations:

$$PT = \{pt_1, \ldots, pt_i, \ldots, pt_n\}, \ n = 7, \ i \in \langle 1; n \rangle, \tag{5}$$

where: pt_i—time of the i-th movement of the robot.

Upon an empirical observation, it was found that in the considered example, the main influence on the total execution time of connections will be the times of supporting tasks. Therefore, the assumed target criterion, which is the function C_{max} can be determined by the following dependency:

$$C_{max} = \sum pt_j + \min \sum pt_k; \ j \in \{1, 3, 5, 7\}; \ k \in \{2, 4, 6\}. \tag{6}$$

To determine the value of the desired objective function, it is necessary to predefine the order of the robot's movement between the points of the workpiece (elements of the set O) with simultaneous consideration of the times of individual movements of the robot (elements of the set PT).

As mentioned earlier in the study, the analyzed problem, due to its constraints, belongs to the NP-difficult class of problems. However, due to an accessible number of scheduling tasks, it is possible to compile alternative scenarios of the robot's work and analyze the times of effective and supporting tasks. This will allow the determination of a schedule that meets the adopted goal criterion, and will also provide a basis for considering further aspects of the robotized welding process for thin-walled structures.

3.3. Robot Movement Scenarios

Due to the limitations of the presented technological requirements, there are several scenarios of robotized weld execution. There are eight possible scenarios in one position, but due to the symmetry of the workpiece wall, the number of work sequences can be reduced to four. The possible robot work sequences are summarized in Table 1.

Table 1. Possible scenarios of the work of the welding robot.

Scenario	Movement Sequence *	
	Part I—Walls Jointing	**Part II—Flange Jointing**
I	AB [e]–BD [s]–DE [e]	EC [s]–CB [e]–BF [s]–FE [e]
II	AB [e]–BD [s]–DE [e]	EF [s]–FE [e]–EC [s]–CB [e]
III	AB [e]–BE [s]–ED [e]	DC [s]–CB [e]–BF [s]–FE [e]
IV	AB [e]–BE [s]–ED [e]	DF [s]–FE [e]–EC [s] –CB [e]

* [e]—effective movement; [s]—supporting movement.

The determination of alternative sequences of robot movements is only the first part of the analysis. The key aspect is the timing of each robot task. While the times of effective movements (to ensure proper weld quality) will be the same in each scenario, the times of supporting movements depend on the length of the path covered by the robot between successive points. For this reason, it was necessary to thoroughly analyze the times of supporting movements of the robot in the analyzed case.

3.4. Analysis of the Times of the Robot Movement

In order to perform an accurate analysis of the time of each robot motion in K-ROSET robot programming and a simulation environment, a model of the production workstation constituting a manufacturing cell was developed, and key points of the robot path were defined—important from the point of view of performing effective and supporting movements (Figure 3). The robot's movements were programmed in such a way that would allow one to fully maintain the real conditions of the process—e.g., supporting movements were planned, taking into account the aspect of avoidance of collision of the robot tool with the workpiece, reaching the weld start point at the right angle, etc.
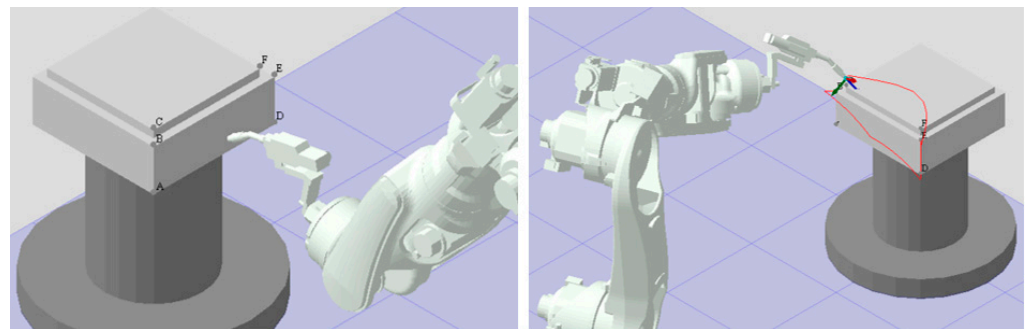

Figure 3. Model of the developed workstation and movements analysis.

Programming of the movements and the simulation of the robot's work allowed one to determine the transit times for each section. The precise determination of the times was possible by using the "Cycle Time" tool, which is one of the elements of the environment used. The obtained results are summarized in Table 2.

Table 2. Times of individual movements of the robot.

Type of Movement	Segments	Designations	Time [s]
effective	AB, DE, ED	t_{AB}, t_{DE}, t_{ED}	22.50
	CB, FE	t_{CB}, t_{FE}	13.50
supporting	BD	t_{BD}	12.10
	BE	t_{BE}	11.88
	DC	t_{DC}	10.27
	DF	t_{DF}	5.89
	EC, BF	t_{EC}, t_{BF}	8.89
	EF	t_{EF}	4.52

Determining the transition times of the robot effector between the successive points allowed one to realise the scheduling process of the individual jobs of the welding robot.

3.5. Task Scheduling of the Welding Robot

The determination of the effective and supporting task times of the robot allowed for the analysis of alternative work scenarios in terms of the considered objective criterion. The

obtained total times of joining the structure with the use of the welding robot are shown in Table 3.

Table 3. The times of individual tasks of the robot depending on the work scenario.

Scenario	Time of the Operation [s]							$\sum pt_j$ $j \in \{1,3,5,7\}$	$\sum pt_k$ $k \in \{2,4,6\}$	C_{max} [s]
	pt_1	pt_2	pt_3	pt_4	pt_5	pt_6	pt_7			
I	$t_{AB} =$ 22.50	$t_{BD} =$ 12.10	$t_{DE} =$ 22.50	$t_{EC} =$ 8.89	$t_{CB} =$ 13.50	$t_{BF} =$ 8.89	$t_{FE} =$ 13.50	72.00	29.88	**101.88**
II	$t_{AB} =$ 22.50	$t_{BD} =$ 12.10	$t_{DE} =$ 22.50	$t_{EF} =$ 4.52	$t_{FE} =$ 13.50	$t_{EC} =$ 8.89	$t_{CB} =$ 13.50	72.00	25.51	**97.51**
III	$t_{AB} =$ 22.50	$t_{BE} =$ 11.88	$t_{ED} =$ 22.50	$t_{DC} =$ 10.27	$t_{CB} =$ 13.50	$t_{BF} =$ 8.89	$t_{FE} =$ 13.50	72.00	31.04	**103.04**
IV	$t_{AB} =$ 22.50	$t_{BE} =$ 11.88	$t_{ED} =$ 22.50	$t_{DF} =$ 5.89	$t_{FE} =$ 13.50	$t_{EC} =$ 8.89	$t_{CB} =$ 13.50	72.00	26.66	**98.66**

Upon analyzing the above scenarios of welding robot operation during the joining of structures in one setting, it should be concluded that the most beneficial, from the point of view of the adopted criterion of the objective, is the scenario II with a sequence of movements AB ^{e}–BD ^{s}–DE ^{e}–EF ^{s}–FE ^{e}–EC ^{s}–CB ^{e} (e—effective movement; s—supporting movement). Consequently, the researched sets O and PT will be defined as:

$$PT = \{pt_1, pt_2, pt_3, pt_4, pt_5, pt_6, pt_7\} = \{22.50, 12.10, 22.50, 4.52, 13.50, 8.89, 13.50\} \quad (7)$$

$$O = \{o_1, o_2, o_3, o_4, o_5, o_6, o_7\} = \{AB, BD, DE, EF, FE, EC, CB\} \quad (8)$$

Scenario II is characterized by the minimum value of the expression $\sum pt_k = 25.51$ [s], which consequently allows one to obtain the value of the adopted objective criterion at $C_{max} = 97.51$ [s]. Due to the constant nature of the times of the effective tasks (welding joints), it is the times of the supporting tasks that significantly impact the values of the C_{max} index, i.e., the completion time of all tasks.

The benefits of the most favorable scenario of the robot's work are most noticeable when compared with the scenario in which the sequence of movements determines the highest value of the objective function (Figure 4). In order to present the obtained difference, the elongation index of the completion deadline of all tasks ΔC_{max}, which is a commonly used indicator for evaluating schedules [11], can be used. In the analyzed case:

$$\Delta C_{max} = C_{maxIII} - C_{maxII} = 103.04 - 97.51 = 5.53 \text{ [s]} \quad (9)$$

where:

ΔC_{max}—elongation of completion time of all jobs,
C_{maxIII}—the task completion date in scenario III (the least favorable scenario),
C_{maxII}—the task completion date in scenario II (the most favorable).

In order to illustrate the differences between the scenarios, they were summarized in the form of Gantt charts (Figure 4).

However, it should be noted that the obtained elongation of completion time relates to the robot tasks only in one setting. Therefore, in the case of the whole process, this difference will increase, and for one workpiece, it will equal $2 \cdot \Delta C_{max} = 11.06$ [s]. Figure 5 compares the robot task schedules in scenarios II and III.

Figure 5 confirms that the analysis of alternative scheduling of the welding robot is visibly beneficial in terms of reducing the process operation time. The obtained time reduction stands at 5.4%.
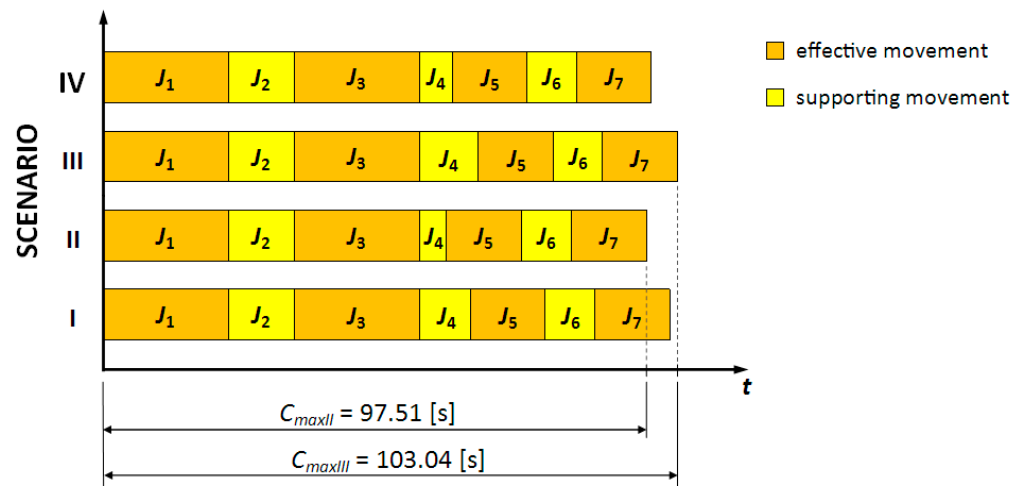
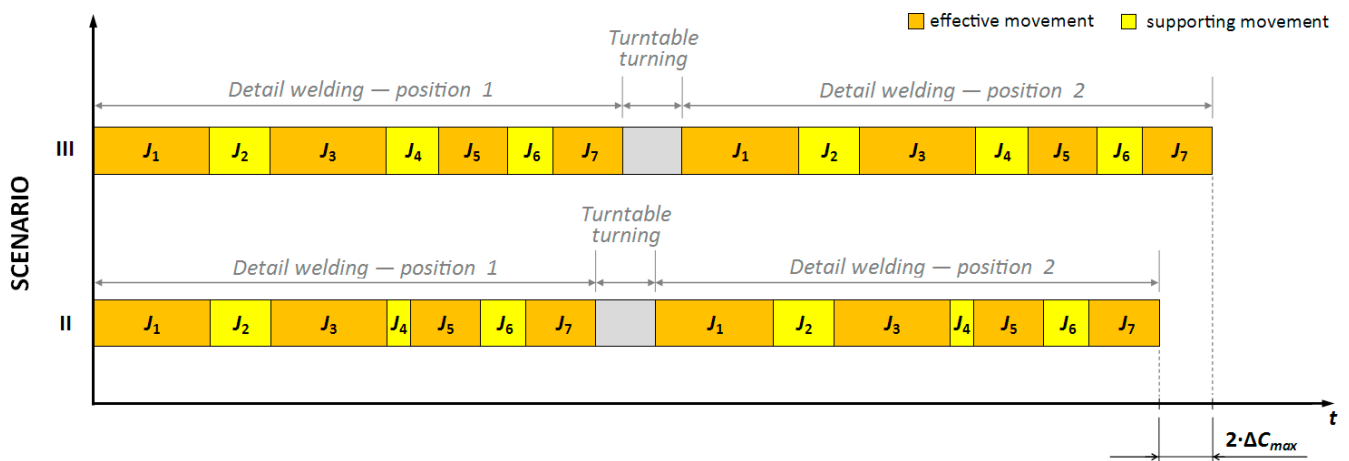**Figure 4.** Schedules of the work of the robot in one position for different scenarios.

Figure 5. Schedules of the robot work throughout the entire process—comparison of the II and III scenario.

3.6. Discussion of the Results

Solving the presented problem from the field of welding robot path selection in the process of joining a thin-walled sheet metal structure allowed one to formulate conclusions.

It should be noted that the benefits of determining the most beneficial work schedule of the robot will be noticeable, especially during the implementation of the production of a larger number of details. The obtained value of technological operation time reduction will result in increased time savings throughout the entire production process. The value of time reduction refers to one piece, so an increase in the number of parts produced will result in a corresponding increase in time savings. Figure 6 shows a graph of the expected benefits of the time reduction during the analyzed process of robotic welding of a workpiece.

Upon analyzing Figure 6, it should be stated that while in the case of the production of tens of pieces, the time saving will be only a few minutes, in the case of the production of a few hundred details, it would amount to hours. From the company's point of view, such time reductions will enable savings in other aspects of production—such as electricity consumption. In addition, the shorter working time of the robot is beneficial in terms of the aspects of its life, such as the wear and tear of joints and other operating elements of the robot.
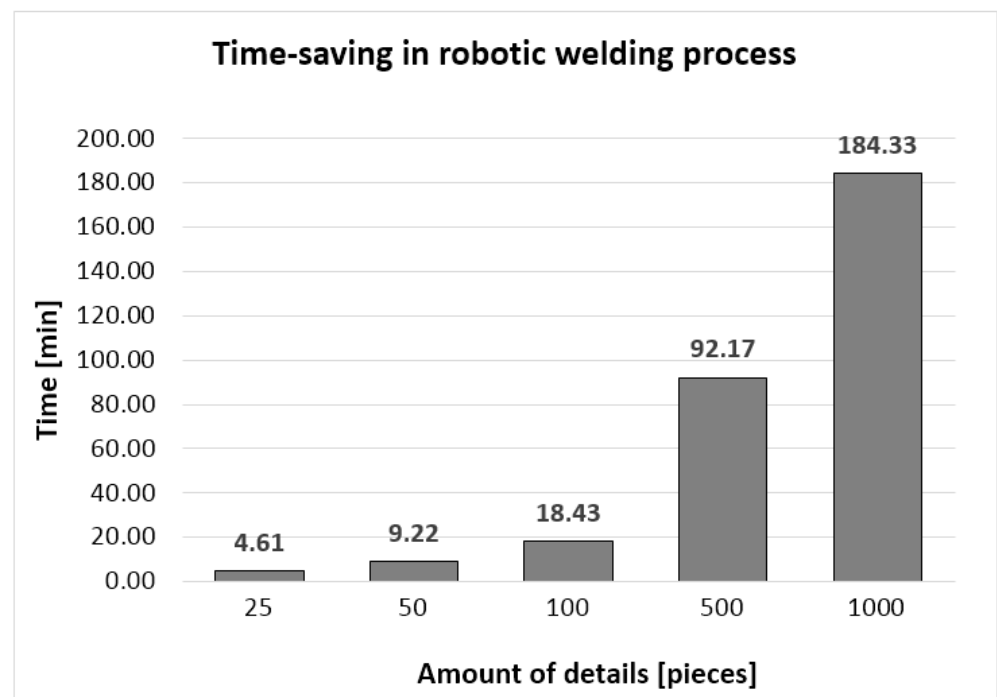
Figure 6. Benefits of the obtained time reduction of the process.

The selection of an appropriate work scenario in terms of the adopted goal criterion is beneficial not only from the point of view of the robotized technological operation, but the entirety of work of producing a given workpiece, as well as the totality of conducted production processes.

The time savings obtained (depending on the number of manufactured pieces) can influence the completion dates of other operations and entire technological processes. Reducing the time of one operation may result in shortening the entire production schedule (speeding up the completion date of production), which in today's highly competitive world may bring measurable benefits to the production company. Figure 7 presents an example of a schedule for three production tasks, which illustrates the benefits of reduction in comparison with other processes. Assuming that station M_3 is a robotic welding cell, the optimization of which is the subject of this paper, and the other machines represent the preceding and following manufacturing cells, respectively, it can be seen that the reduction in robotic operation time will affect other processes. As a result, it will shift the start times of selected operations (e.g., operations 1.4 or 2.4), shorten the end times of operations (e.g., operations 1.5 or 3.4), and even change the completion date of all production tasks.

The optimized scheduling of effective and supporting tasks of an industrial robot while considering the existing limitations of the process is an extremely important issue, and the benefits resulting from this process affect many aspects of production execution.
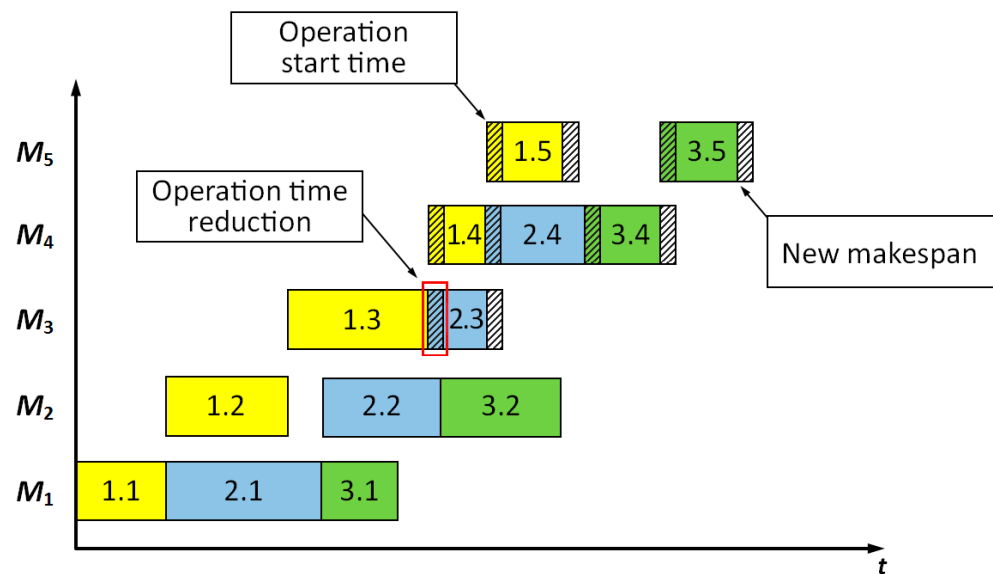
Figure 7. Time reduction for a robotic operation—influence on other processes.

4. Conclusions

Robotic processes, like other manufacturing processes, require careful analysis. The implementation of an industrial robot alone will not improve the whole process. Relying solely on the integrator's intuition may result in the robot not being used to its full potential. The benefits of its implementation will be negligible or low. Therefore, it is necessary to strive for a detailed analysis and improvement of robotic production processes while taking into account their limitations.

This paper presents a solution to the problem of scheduling a welding robot in the process of joining a thin-walled sheet metal structure. Taking into account the existing limitations resulting from the technology, which in the literature are often neglected during the analysis of robotic processes, the most advantageous work schedule was determined, assuming as the criterion of the goal the time of completion of all robot tasks in one workpiece position (completion of all joints)—determining the sought solution allowed the development of a schedule for the entire process, as well as an indication of the benefits of the obtained time reduction. On the basis of the results obtained, a summary of the expected time savings in the process was prepared, as well as their impact on other aspects of production. The important role of the makespan of robotic operations, which can affect the entire production process, was also emphasized. Time-saving means freeing up resources, increasing the availability of machines, and consequently completing other orders at an earlier date.

The solutions presented in the paper are the introduction of the problem of robotic production processes optimization under constraints. In further research, there is a need to take into account other aspects influencing the optimization of the work of robotic production stations—e.g., optimization of the robot effector trajectory, minimization of the distance between the elements of the workstation, robot energy consumption, variability of the robot speed. Additionally, the analysis of problems with greater computational complexity and different process characteristics should be considered. There is a need to develop appropriate optimization methods and algorithms searching for solutions to the presented problems in an accessible time. The presented problem of robotic movement scheduling should be extended to current trends in robotics—e.g., cooperation between robots, collaborative robot utilization, or the robots' resources allocation (e.g., grippers).

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