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A simulation-based approach to study the influence of different production flows on manufacturing of customized products

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A B S T R A C T

Manufacturing products tailored to the individual requirements of customers is a must if companies want to compete effectively on the market. The production of customized goods poses new challenges for all areas of functioning of production systems. It is necessary to adopt such rules and methods that will allow a flexible response to product design changes and their demand In the organization of production flow (materials and information). The article presents research carried out in the SmartFactory laboratory of the Poznań University of Technology regarding the impact of the structure of products (customization) on the realization of current production orders. The research was carried out using the FlexSim simulation environment. Based on simulation experiments for three forms of organization of production flow with varying degrees of flexibility of production resources, an analysis was made of the time of execution of various sets of production orders and the level of use of available working time. The results of research indicate that in the production of products with low and high planned labor consumption, the use of universal production station is the most advantageous. For such a solution, the degree of utilization of the available working time of production stations is also the highest. It was also found that the principles of scheduling production orders affect the effectiveness of the production system. The best results were obtained for the production schedule, where the sequence of production orders was established from the lowest planned time of resource loading.

A R T I C L E   I N F O

Keywords:
Smart manufacturing;
Production flow;
Customized products;
Variant products;
Discrete-event simulation (DES);
FlexSim simulation modeling and analysis software

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1. Introduction

Manufacturing companies try to meet growing demands and changing customer demand in various ways. Some of them try to improve production processes by implementing various concepts, e.g. Lean Manufacturing or Six Sigma, so as to be able to produce products of the required quality in a short time and at relatively low costs [1]. Others, however, decide to manufacture products designed for individual customer orders, i.e. mass customization (MC) [2]. The term mass customization was first used by Stan Davis in Future Perfect [3] and then developed by Pine II [4]. In this paradigm it is extremely important to offer products tailored to individual customer needs while maintaining mass production efficiency [5-7]. The purpose of mass customization, however, is not to provide different product variants, but to design the product in accordance with the individual requirements of the recipient [8]. The implementation of mass customization is very attractive from the customer's point of view, but for the company it creates the risk of failure, especially due to the increase in costs of designing and manufacturing products. The MC strategy can give a competitive advantage on the market only if the company is able to quickly respond to changing expectations and requirements of customers, i.e. it is able to combine the MC strategy with the Quick Response (QR) strategy. The combination of both strategies is only possible if the company has a flexible production system (including flexible production resources) and is able to quickly design and implement new products and their manufacturing processes [9-12].

Mass customization is also one of the basic goals of industry 4.0 [13, 14]. Industry 4.0 refers to the Digital Manufacturing System provided by the effective integration of production processes, information technologies and equipment [15, 16]. The main goal of industry 4.0 is to improve the efficiency and reactivity of the production system [16]. In industry 4.0, production processes must also be more flexible, combining high efficiency and diversity of the production range, and intelligent to be able to successfully meet the challenges of dynamically changing demand and individual customer needs [18-20].

A measure of the flexibility of the production process is its ability to perform operations, as well as the "speed" at which it can be prepared to perform a new task. However, a high degree of production flexibility causes problems with organization and production control [21-24]. These problems result primarily from the dynamic conditions of customer demand, the production of various products and the failure to use the available production capacity of production resources. One of the factors affecting the use of the available production capacity of machines and technological devices in flexible production systems is the degree of specialization of workstations [25]. This means that in the case of flexible production processes, the use of special and specialized work stations (i.e. having dedicated equipment for the production of specific types of products and production operations on these products) carries the risk of not using the available production capacity of these stations [26]. Therefore, in the case of mass customization strategies, universal work stations that can carry out different production tasks on different products are more often used. These universal work stations can be assembled into a production line, manufacturing cell or take the form of a workplace organization of production [27].

In turn, dynamic conditions of demand and the production of various, customized products force production companies to look for the best solutions in the field of organization and control of production. To this end, many of them decide to use simulation methods that allow the analysis and evaluation of different variants of the organization of production flow [28, 30, 31]. The term "simulation" means imitating the real situation, real objects and connections that exist between these objects [29, 32]. Simulation is a research method and enables research, analysis and evaluation of introduced changes outside of real processes [33, 34]. In a simplified way, the simulation is carried out in three steps [35]:

- designing the simulation model of the actual process or system,
- conducting experiments using the simulation model,
- using the results obtained to improve the actual system or process.

Simulation models of manufacturing processes are built to reduce the risk of failure when making significant changes to the actual process or when designing a new process to be able to choose the best variant of the organization of production. The simulation allows you to gain insight into complex process structures, test new rules for the organization of production, or flow of materials through the process, analyze production indicators or collect information and knowledge without violating the actual process [33, 36].

This article presents the results of research aimed at determining the impact of the form of the organization of production flow on the efficiency of the set of production orders for customized products (with different construction structure). Three groups of products were adopted, different in terms of labour intensity of performance. A series of simulation experiments were carried out for three samples of production order sets implemented in three variants of forms of organization of production flow: linear, cell and station. In addition, each set of orders was subjected to experiments taking into account different rules for scheduling orders: in any order, from the longest to the shortest and from the shortest to the longest. The obtained results were analyzed in terms of the time of order completion and the degree of use of the available work time of the workstations.

2. Problem presentation and a goal of the research

2.1 SmartFactory laboratory at Poznan University of Technology

The production system at the SmartFactory laboratory of the Poznan University of Technology was built to conduct research works for various technical and organizational solutions in line with the concept of Industry 4.0. The laboratory equipment allows mapping of various processes occurring in the real production system.

Research work carried out in the laboratory focuses on:

- development of systems supporting the design and configuration of customized products,
- additive production of parts and production instrumentation,
- application of virtual reality and augmented reality solutions in production and training processes,
- development and testing of methods and information systems supporting production planning and control,
- implementing technical solutions to supervise and control material flow, e.g. RFID, RTLS.

The main element is the automatic assembly line. It consists of three transport loops at which work stations are located. The loops are equipped with switches that enable the redirection of the pallet being the carrier transporting the product to any transport loop. Each pallet has an RFID tag enabling its identification and directing its movement by the RFID head reading and switches steering. The line is controlled by a control cabinet equipped with power elements, protection systems, power supply, PLC controller, and security system module. The system uses two industrial networks AS-interface and ProfiNet for controlling devices.

Production system management is carried out by an IT system called 4Factory. Communication between system elements takes place via the Internet of Things. The 4Factory system is built of a number of modules whose functionalities enable production planning, supervision of material flow, and control of the production line operation (Fig. 1).

The production process in the SmartFactory laboratory involves the assembly of parts products in the form of lego blocks. They were adopted as a basic element of the construction of finished products so that the flexibility was provided in the field of product construction in accordance with the idea of customization of production. The flow of products on the production line is carried out according to the principle of one piece flow, where a transport pallet is the carrier. Work stations are equipped with flow racks that allow storage of containers with parts and assemblies for assembly of finished products. The shelves were also equipped with RFID reading heads enabling their identification. The basis for starting the production process is the schedule developed in the 4Factory program. It provides information about the order of production of products and their assembly sequence at individual positions. The assembly process is carried out manually by operators who carry out tasks in accordance with the schedule and assembly instructions.

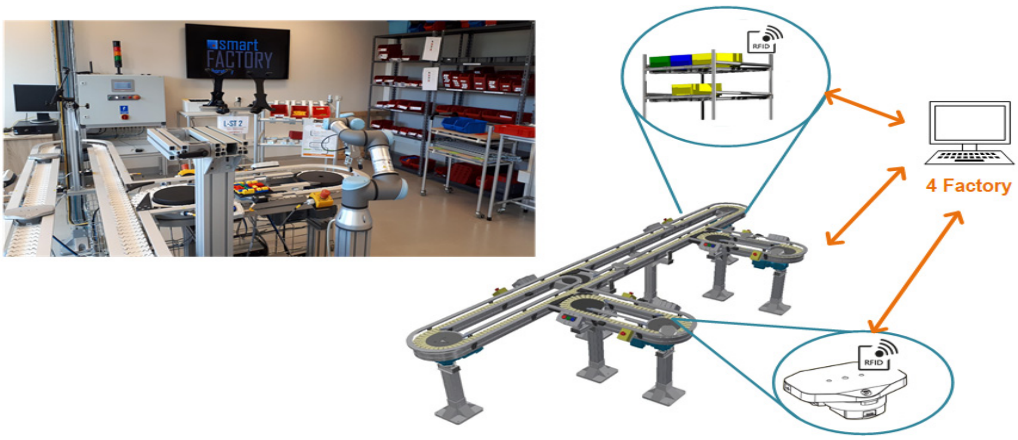

Fig. 1 View and visualization of the SmartFactory laboratory

2.2 The aim of the test

The technical equipment and possibilities in the scope of product construction influence the high flexibility of the production system. Therefore, one of the research directions is the development of a dynamic method of scheduling and controlling production flow for high variability of product variants (customized products). The presented research is one of their stages.

The aim of the research was to determine the impact of the form of the organization of production flow on the efficiency of the realization of a set of production orders for products with different constructional structures.

The study assumed three variants of the production flow form (Fig. 2):

- Variant 1 (variant 1-6): linear form – the production process for each product is carried out at all six subsequent workstations.
- Variant 2 (variant 1-2-2-1): nest form – the production process of a given product is carried out at station 1, manufacturing cell 1 or 2 containing two stations and station 6.
- Variant 3 (variant 1-4-1): workplace form – the process of producing a given product is carried out at station 1, then at one of the universal stations from 2 to 5 and station 6.

18 different parts with different numbers and assembly configuration were the basis for the construction of product variants. In this way, products with different constructional structures and thus different planned load times for work stations are created. The standard assembly time for one part is 4 [s], and the same time to manufacture 1 piece of product is a multiple of this time and the number of pieces of product components.

Variants 1-6 include the assumption that each product with any constructional structure is implemented at all six subsequent work stations. At the given work station, 3 types of parts that are assembled are strictly defined.

Variants 1-2-2-1 assume the occurrence of 2 mutually replaceable manufacturing cells consisting of two stations. In this variant, stations 1 and 6 provide for the assembly of parts as in option 1, while the assembly of other parts is possible in manufacturing cells.

Finally in variant 1-4-1, at stations 1 and 6, the assembly of parts is carried out as in the previous variants. Stations 2 to 5 are replaceable/universal, where it is possible to install other parts.

The presented scope of tests was conducted in the FlexSim simulation environment and the obtained results were the basis for developing the production schedule in the 4Factory program, controlling the assembly line in real conditions.

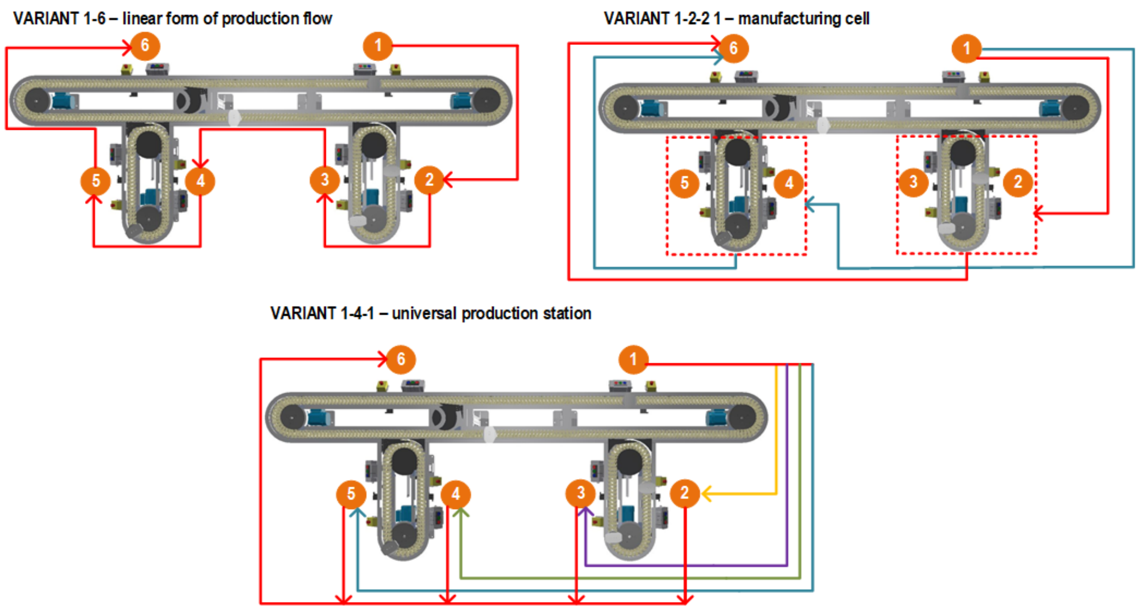

Fig. 2 Schemes of variants of forms of organization of production flow

3. A simulation-based approach

The research involved conducting a number of simulation experiments in the FlexSim environment and included the implementation of production order sets for the assumed three variants of the organizational form of production flow. They were carried out according to the following stages: execution and verification of simulation models of variants of production flow forms, design of products and their technological processes, development of sets of production orders, conducting simulation experiments, and analysis of results.

3.1 Simulation models of different forms of production flow

Simulation models for the SmartFactory laboratory reflected all the necessary technical and functional elements of the production system. Objects representing the necessary elements of the production process (e.g. order list) but also technical elements ensuring the proper operation of the models have been implemented. These elements include tables containing parameters and results of the model's operation as well as objects visualizing its operation. An example of the visualization of the simulation model for one of the variants of the form of organization of the flow is shown in Fig. 3.

The operation of the simulation model is determined by the parameters contained in the "parameters" table. This table contains both general parameters for the model and detailed parameters for each of the products. The list of production orders is represented in the model in the form of an appropriate table of the "orders" object - a single row in this table represents one order and contains the following parameters: product name, order size, and sequence of its execution. The results of the model operation are represented by output tables, messages in the simulator console window, and graphs updated during the model operation.

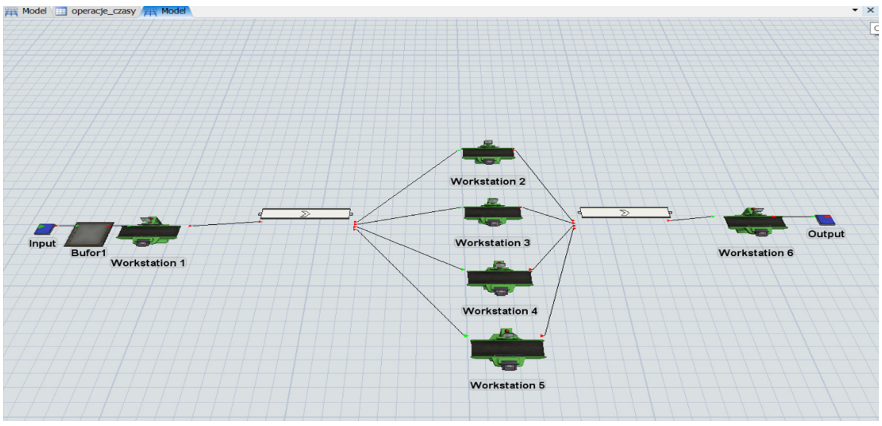

Fig. 3 Schemes of variants of forms of organization of the flow of production

3.2. The aim of the research

The study assumed the existence of three groups of products with different numbers of components forming the constructional structure and thus with different planned load times for work stations. This time is understood as the required standard lead time for assembly tasks at all work stations. Product groups were defined as:

- products with a small planned load time – products containing 10 to 20 parts,
- products with an average planned load time – products with 20 to 40 parts,
- products with a high planned load time – products containing from 40 to 70 parts.

For each product group, 30 structurally different products were designed and technological processes were developed for them, taking into account the assumed variants of production flow.

Product groups were then the basis for generating sets of production orders to be implemented in simulation models. Three sets of production orders were generated for each group of products:

- for products with low labor intensity (designations L 1-3),
- for products with low average labor consumption (designations M 1-3),
- for products with low high labor consumption (designations H 1-3),

which differed in the occurrence of product variants, in their share in the collection and in the number of pieces.

Sets of production orders included restrictions:

- the maximum number of items in the set of production orders: 100 items,
- the number of items in the production order: 5-20 items,
- the number of production orders in the set: 30,
- production orders in the set may refer to a given product many times.

Table 1 presents the general characteristics of production order sets.

Table 1 Characteristics of production order set

Set of orders	Total planned time load workstation	Minimum planned duration of load workstation	Maximum estimated time of load work-station	Minimum number of pieces	Maximum number of pieces
L1	246,67	3.33	17.33	5	20
L2	248.93	3.33	17.07	5	20
L3	238.13	3.33	15.20	5	19
M1	682.07	12.00	47.50	5	20
M2	682.80	13.53	48.00	5	19
M3	674.53	12.00	40.53	5	19
H1	1293.73	41.33	84.00	5	20
H2	1294.93	44.80	88.00	6	20
H3	1290.93	41.67	79.80	5	19

3.3. Simulation experiments

Simulation experiments were carried out for three samples of each of the production order sets with the characteristics described above for each variant of the organization of production flow. Each set of orders was also subjected to experiments taking into account different rules for their ordering (establishing the order of implementation in the production schedule), namely: in random order, from the largest to the smallest and from the smallest to the largest planned load time of work stations. In total, 81 simulation experiments were carried out.

In the research, the production execution time was assumed as the main indicator for the assessment of production flow variants. However, the degree of utilization of the available working time of work stations was also introduced as an additional indicator.

4. Results and discussion

4.1. Production order processing time

The results of the research were the result of simulation tests. The analysis of these results included the time of execution of production orders and the degree of use of the available working time at work stations.

The production order group execution time covers the period from the beginning of the first operation of the first order to the end of the last operation of the last order included in the production schedule.

Based on the analysis of the results, it can be concluded that for products with a small planned load time, the shortest order fulfillment times were obtained for variant 1-4-1 of the form of production flow for three samples and for three rules for order scheduling in the production schedule. The linear form (variants 1-6) turned out to be the worst for all three sets of orders and each of the three variants of the production schedule. Data analysis also showed no significant impact of scheduling on order processing time (Fig. 4).

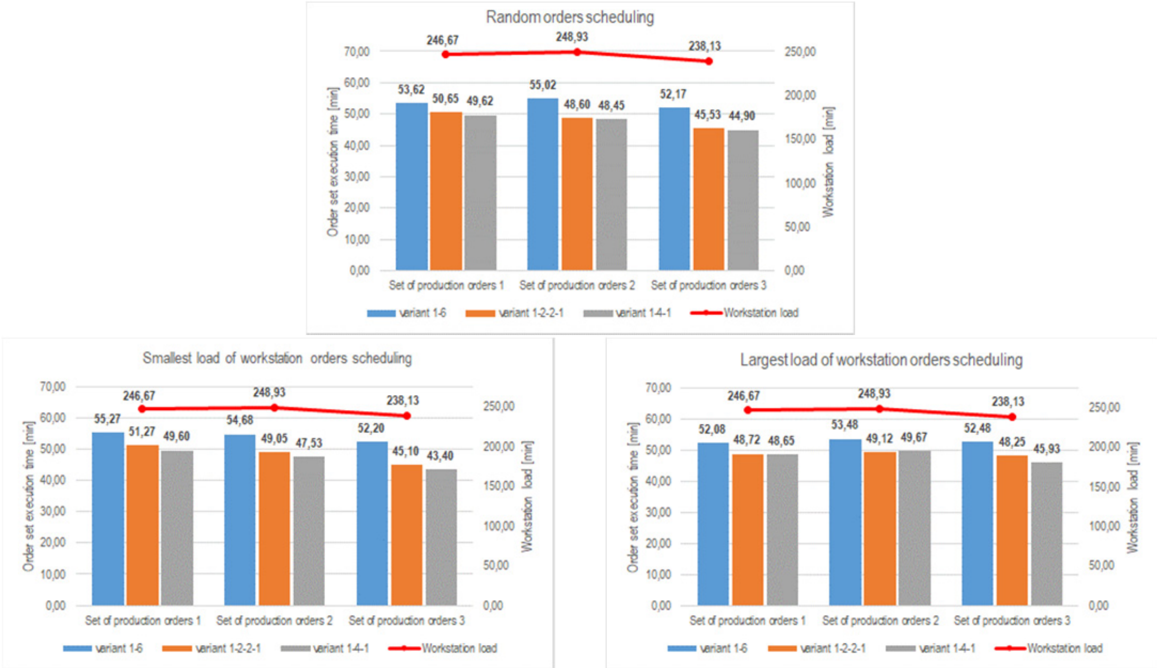

Fig. 4 Comparison of production order fulfillment times for products with low planned resource load

For products with an average planned load of workstation, the time of order sets are comparable for all three variants of organization of production flow. The analysis did not show in this case a significant correlation of the analyzed factors. Only a comparison within a given set of production orders allows to indicate the best variant. For the set of orders 1, the results are comparable with the indication for option 1-4-1. Variant 1-2-2-1 allows the shortest order fulfillment time for the set of orders 2 and 3 (Fig. 5).

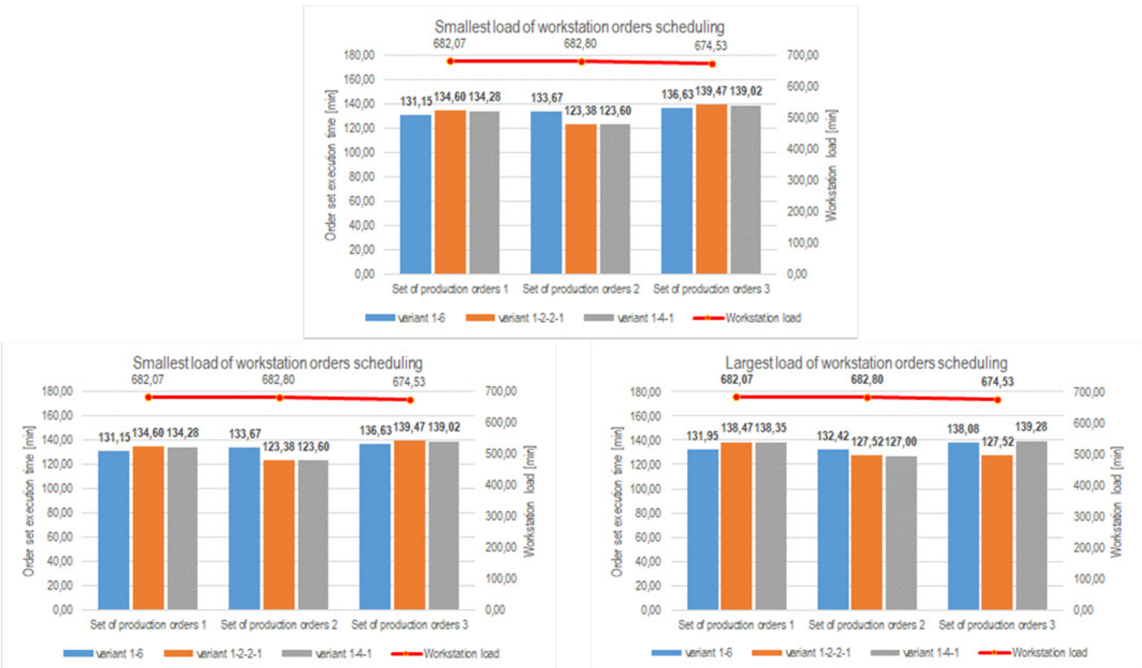

Fig. 5 Comparison of delivery times for production orders for products with average planned resource load

For products with high planned load of stations, the shortest times were obtained in option 1-4-1 forms of production flow for three samples and three rules for order scheduling in the production schedule. The linear form (variants 1-6) turned out to be the worst for all three samples and for each of the three variants of the production schedule. Analysis of the results indicates that for variant 1-6 the shortest times were achieved in the case of order scheduling from the lowest load time for work stations. However, in the case of variants 1-2-2-1 and 1-4-1, the shortest order fulfillment times were obtained for scheduling with the largest planned load of positions (Fig. 6).

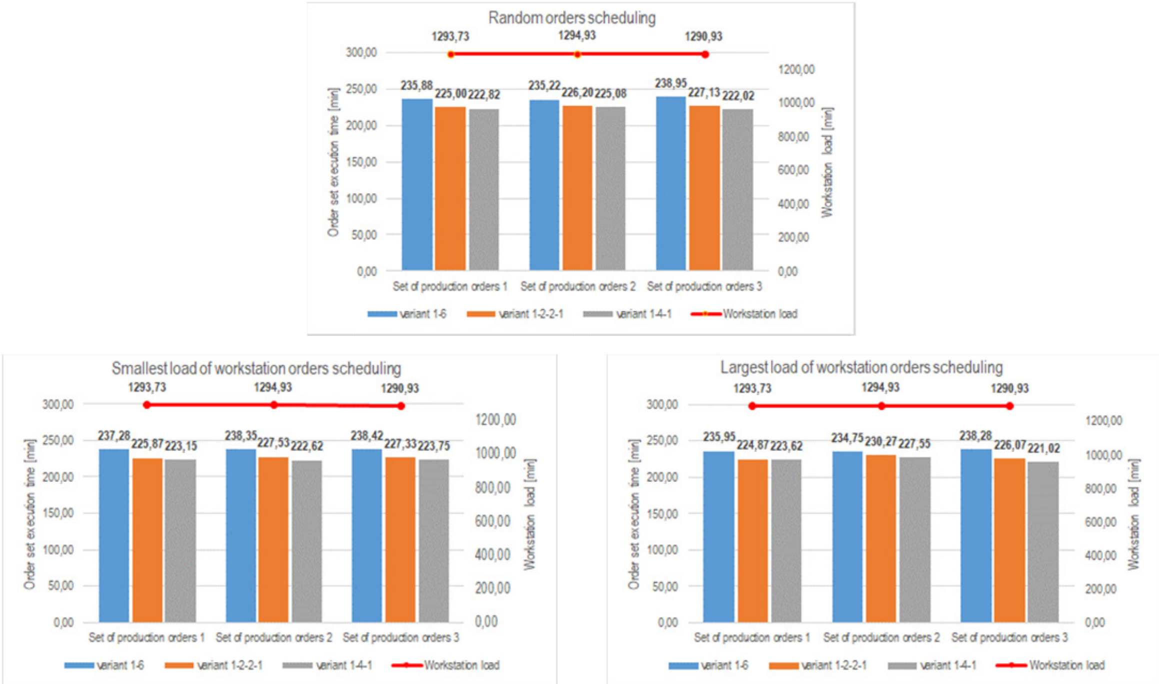

Fig. 6 Comparison of delivery times for production orders for products with high planned resource load

4.2 Use of available working time

The reference value for analyzing the degree of use of the available working time of work stations was the time of implementation of a given set of production orders.

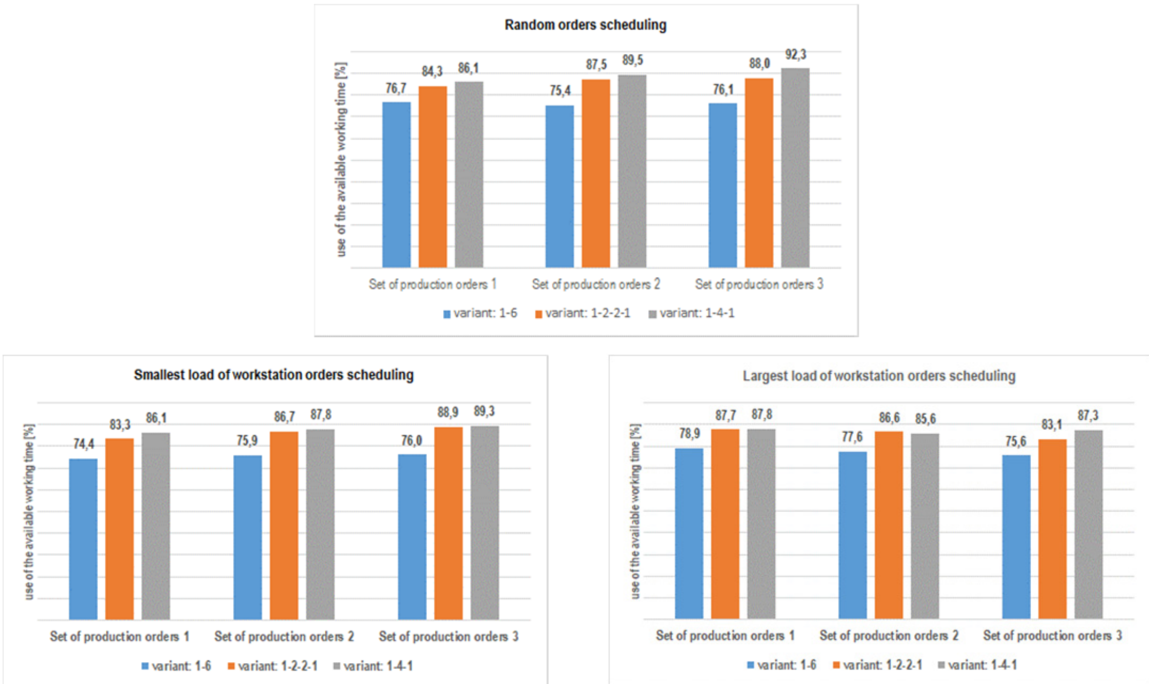

Fig. 7 Comparison of the use of available working time for products with low planned resource load

For orders with a low planned load on work stations, the largest use of available working time was obtained for the variant 1-4-1 of organization of production flow. Similar values were obtained for variant 1-2-2-1, while variant 1-6 has the lowest level of use of available working time. These results apply to all rules for scheduling the implementation of production orders (Fig. 7).

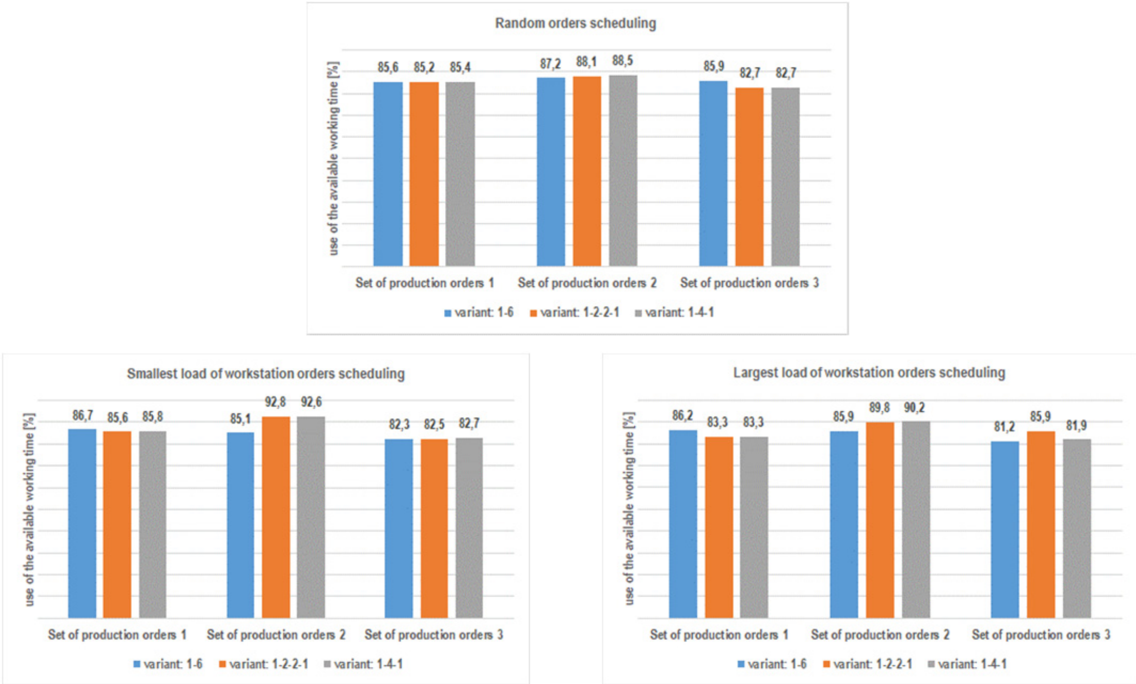

Fig. 8 Comparison of use of available working time for products with average planned resource load

Simulation experiments for sets of orders with an average planned load time of production positions did not indicate clear correlations between the examined factors. In the case of random orders, the results are comparable for each variant of the organization of production flow. Variants 1-2-2-1 and 1-4-1 allow to obtain slightly better results for production schedules set according to the rules from the smallest and the longest planned load time of work stations, Fig. 8.

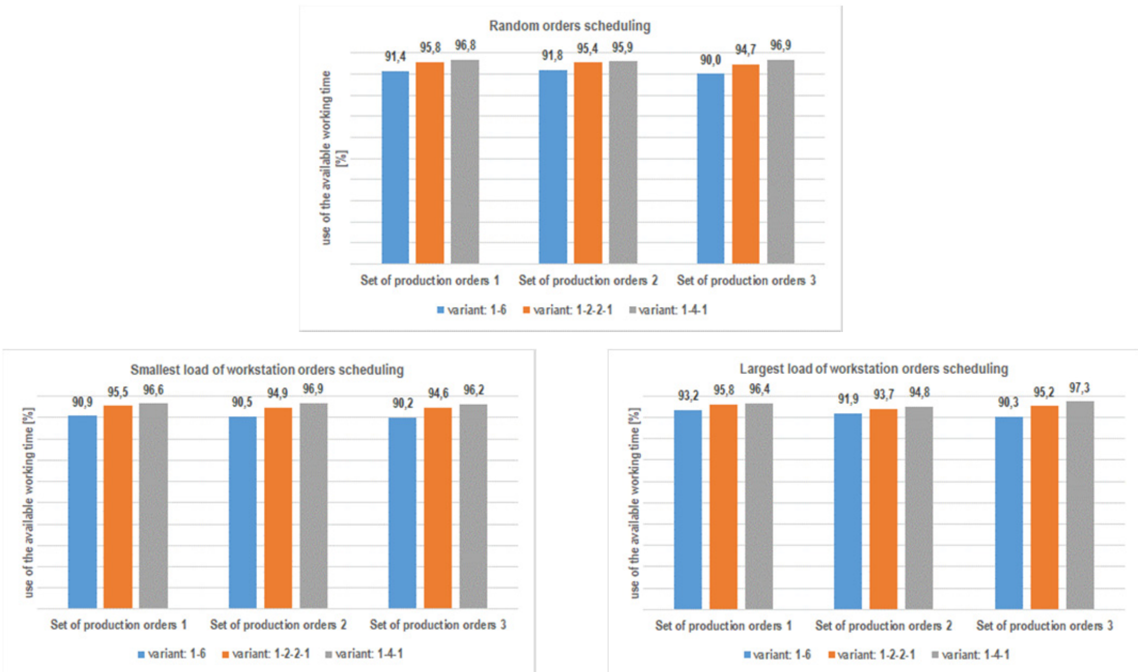

Fig. 9 Comparison of the use of available working time for products with high planned resource load

Analysis of results for order sets with high planned load of stations, the largest use of available working time occurs for variants 1-4-1 of organization of production flow. Similar values were obtained for variant 1-2-2-1, while variant 1-6 has the lowest level of use of available working time. These results apply to all rules for scheduling the implementation of production orders (Fig. 9).

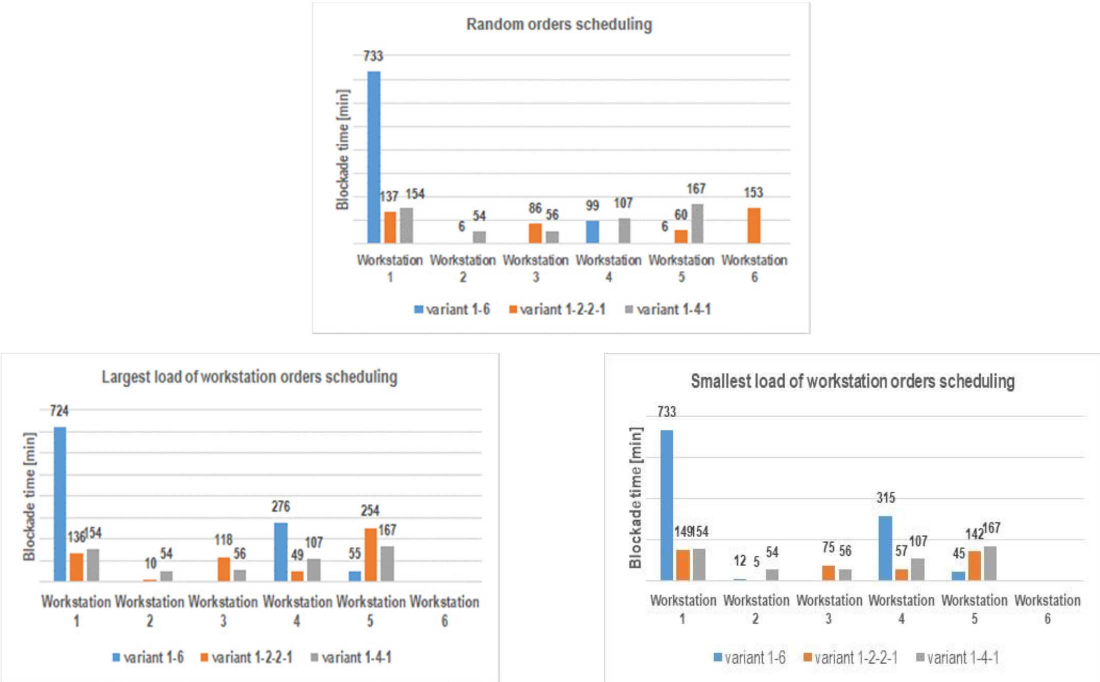

Fig. 10 Production system blockade for products with low planned resource load

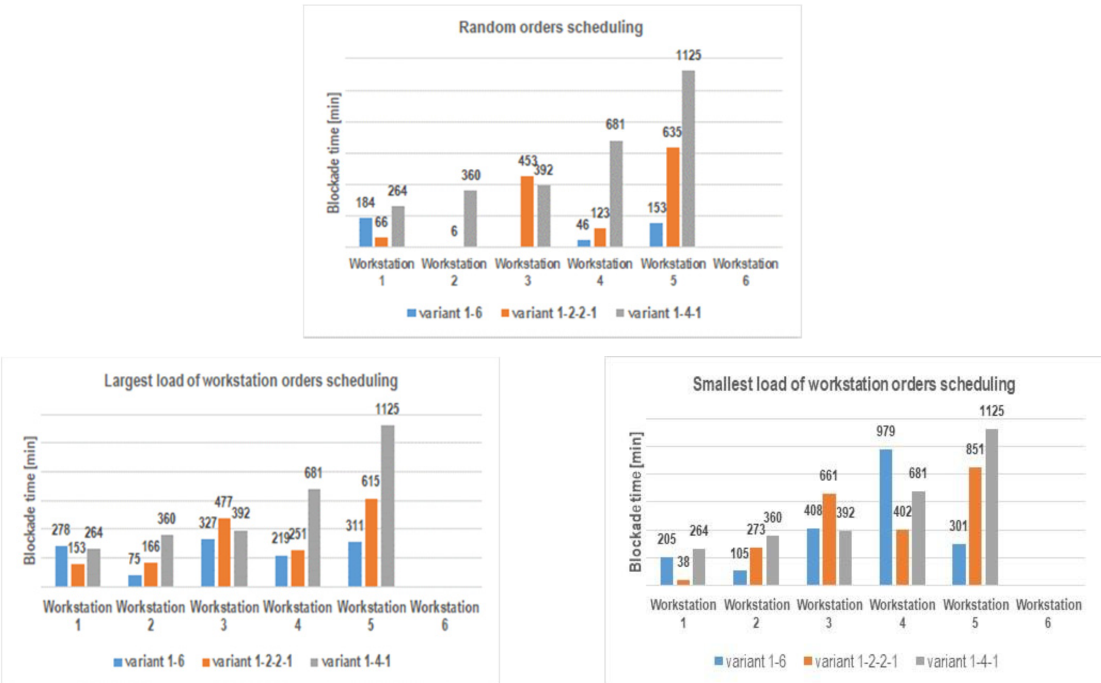

Fig. 11 Production system blockade for products with average planned resource load

The basic factor affecting the degree of use of the available working time of work stations was the so-called "blockade". It refers to the situation in which it is not possible to continue with the production orders for a given position due to the occurrence of the maximum level of inter-operational stock. This is due to the technical limitations of the assembly line, as mentioned earlier, where a maximum of 10 transport pallets (product carrier) can be on a given transport loop between stands.

The results of the simulation experiments carried out indicate that:

- in the case of production orders for products with a low resource load time, station 1 of variants 1-6 most often had downtime caused by blockade for all three types of production schedules (Fig. 10),
- for orders for products with medium load time the longest downtime occurred at stations 4 and 5 for all variants of the organization of production flow (Fig. 11),
- the execution of orders for products with a high resource load time in variants 1-6 and for all variants of their scheduling resulted in stops of positions 2 and 3 (Fig. 12).

The reason for such states of operating of the production system is the lack of load balancing of work stations and synchronization of product flow for the production line.

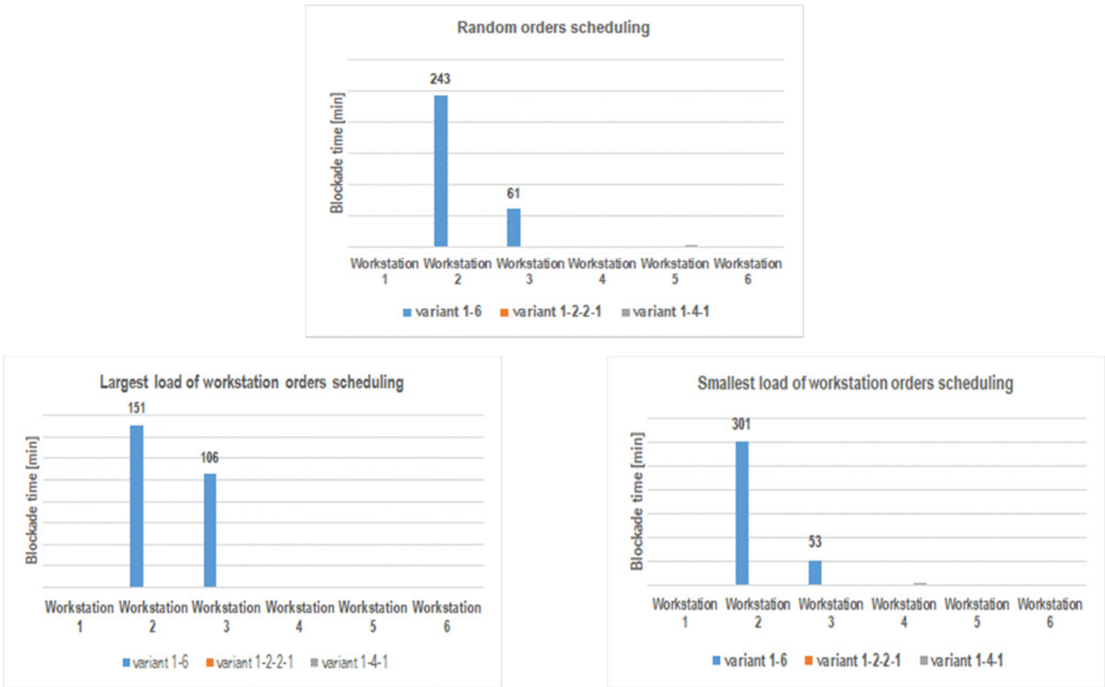

Fig. 12 Production system blockade for products with a high planned resource load

4.3 Comparison of the results

A summary of the results of the tests is presented in Table 2. It contains a summary of average parameter values of assessment for three sets of production orders.

Based on these values it can be concluded that the use of universal positions in the production system (variants 1-4-1 form of organization of production flow) allows to shorten the time of implementation of production orders for products with small and large planned resource load time. For such solution, the degree of utilization of the available working time is also the highest. The obtained results of the effectiveness of functioning of the production system are influenced by the rules for scheduling production orders. The best results can be obtained for the production schedule, where the schedule of work is set starting with the orders with the lowest planned resource load time.

Table 2 Summary of test results

Orders with low planned resource load time									
Assessment parameters	Random order scheduling			Ordering from the shortest resource load time			Ordering from the longest resource load time		
	1-6	1-2-2-1	1-4-1	1-6	1-2-2-1	1-4-1	1-6	1-2-2-1	1-4-1
Order processing time [min]	53.60	48.26	47.66	54.05	48.47	46.84	52.68	48.69	48.08
Utilization of available working time [%]	76.1	86.6	87.7	75.4	86.3	89.3	77.4	85.8	86.9
Orders with average planned resource load									
Order processing time [min]	135.79	134.74	134.47	133.82	132.48	132.30	134.15	131.17	134.88
Utilization of available working time [%]	85.2	85.3	85.5	84.7	87.0	87.1	84.4	86.3	85.1
Orders with high planned resource load									
Order processing time [min]	236.68	226.11	223.31	238.02	226.91	223.17	236.33	227.07	224.06
Utilization of available working time [%]	91.1	95.3	96.5	90.6	95.0	96.6	91.8	94.9	96.2

The variant of organization of production flow based on universal manufacturing cells (variant 1-2-2-1) allows to obtain the best results of order processing time and the degree of use of work stations in the manufacturing of products with medium load time. In this case, it is also beneficial to set the order of execution of orders from those with the largest planned load time. This variant also gives results slightly worse than variant 1-4-1 in the production of products with different characteristics.

The use of a linear form turns out to be the worst solution in the production of this type of products with constructional and quantitative characteristics as adopted in the research. However, for products with an average resource load time, the simulation results obtained do not differ significantly from the other variants of the form of organization of the production flow.

5. Conclusion

Production flexibility is a basic feature of production systems that allows meeting customer requirements in the manufacturing of customized products. The article presents the results of research on determining how the form of organization of production flow affects the implementation of production orders.

The research were carried out in the FlexSim simulation environment and constitute the beginning of research works related to the use of simulation methods in production control. The results of the simulation experiments for the set of production orders, technological processes and evaluation parameters for the analyzed variants of the production system were obtained in a very short time. Nevertheless, it should be borne in mind that the amount of input data and the complexity of the production system will increase the time it takes to obtain simulation results. This is also indicated by the authors' research in research projects commissioned by companies, where the results of simulation experiments were obtained after a few hours. This is undoubtedly a critical factor to consider when applying simulation methods to operational production control.

The indicated results indicate a direct correlation between the flexibility of used production resources and the time of order processing. According to the concept of the Intelligent Factory, production resources constituting a key factor in the manufacturing of products should be based on modularity in order to obtain the possibility of flexible configuration depending on the needs determined by design and technological changes in the manufacturing of products.

Undoubtedly, this flexibility of resources will contribute to increasing the use of their available working time and thus affect their efficiency. Finally, flexible and replaceable production resources will allow for faster and comprehensive execution of customer orders, especially for customized products. And this will have an impact on the increase in the competitiveness of enterprises.

The SmartFactory laboratory is a research facility that allows for testing various technical, IT, and organizational solutions and analyze their impact on the efficiency of the production system. The presented subject and scope of research is related to ongoing works in the field of dynamic production control methods. Research results also indicated directions for further work that will be related to the implementation of production for products with even greater assortment and quantity.

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