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AN EXTENDED PRODUCTION PLANNING MODEL BASED ON THE SIMULATION OF HUMAN CAPABILITIES

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Abstract. Digital mapping and modelling of the real systems in digitization solutions of Industry 4.0 are increasingly contributing to rising of the efficiency of production processes. The complexity of production and logistics systems is further increased by human resources, whose production capacity greatly influences the production process. This paper presents a flexible manufacturing system where employee skills affect system productivity. The values of performance indicators can be changed in a favourable direction using a discrete event-driven simulation model. This model uses an integrated, self-developed module that supports production scheduling and takes the production capabilities of workers into account for better use of the resources in the production system.

Keywords: simulation, production scheduling, human capabilities, digital model

1. Introduction

The common feature of the production companies – both multinational companies and SMEs – is that management aims to serve the customer needs to the highest possible standard, while fulfilling orders with short lead times and ensuring appropriate quality conditions [1]. The large number of orders results in a drastic increase in the number of finished product types. This has an impact both on the design of production systems and the operation of production and logistics processes. On one hand large-scale production is replaced by small and medium-sized series, on the other hand systems supporting production for individual needs are becoming more and more important, where the "one-piece" material flow will be dominating [2]. Meeting these needs can only be achieved with a high degree of flexibility and coordinated operation of the production and the logistics system. Opportunities offered by the Industry 4.0 solutions highly support this through the extensive cooperation of information and communication technologies (ICT), digitization and virtualization technologies [3]. Digital mapping of production and logistics processes of real production systems and the corresponding simulation based studies support the detection of bottlenecks [4]. Mapping of real processes is realized in the digital model at an abstraction level where evaluation of indicators characterizing the operation of the system and examination of influencing parameter values becomes possible [5]. Experiments by changing input parameter values can be performed in digital models, while leaving the smooth operation of real processes intact.

The importance of using simulation studies is increasing: a general model designed to solve a real problem contains several parameters which can be used to examine different operational strategies or to redesign system processes. The examined systems typically consist of discrete production and related logistics processes. Special softwares are available for modelling of these systems digitally. One of these is Tecnomatix Plant Simulation from Siemens, Plant Simulation is a general discrete-event-driven simulation development environment. It supports modelling and simulation of production, manufacturing and logistics processes with a wide set of objects [6], [7]. Using the SimTalk programming language, own algorithms, control procedures and functions may be created to support more realistic, detailed mapping of processes [8].

A common feature of most discrete manufacturing processes is that the operations must be performed on certain machines or workstations in a predefined order on the workpieces. One typical basic manufacturing scheme is the so-called "flow shop" (one-way) model, in which the same operations must be performed on the workpiece sets (jobs) in the same order on the same resources. There may be additional subcategories to this like the passing and no-passing versions. In the no-passing version, the execution sequences of jobs for machines can be different. In the passing version, only one execution sequence is given for all machines [9], [10], [11]. Another typical scheme is the "job shop" model, where each job can have a unique sequence of operations to be performed [12]. Both models may be flexible. If a group of machines is able to carry out an operation, then a machine-assigning process is also needed beside the job-sequencing task [13], [14], [15]. Even with a small number of machines, creating an optimal schedule with a polynomial runtime is not possible due to the complexity of the problem: the vast majority of models fall into the NP-hard problem class. In such cases, it is advisable to use fast heuristic, metaheuristic and search algorithms that give near-optimal solutions in a short runtime [16]. Development of complex models is necessary to support the production scheduling of real production systems, where the parameters, influencing factors and stochastic effects related to the logistics processes are also considered in addition to the parameters occurring in the production process.

Our research work summarized in this paper was induced by a real problem of a flexible assembly system. The following sections present a simulation model and a new heuristic scheduling algorithm for preparing daily production plans with the highest possible performance. The specialty of the system is that the model includes the individual assembly capabilities of human resources (persons). This extension further increases the complexity of the problem. The efficiency of our extended decision-making algorithm is verified by simulation running results.

2. Problem description

2.1. Operations and workplaces

Nowadays, increasing the competitiveness of companies plays a top priority in fulfilling customer orders in time. Besides, maximizing the performance of production processes, minimizing non-productive logistics processes, and reducing losses are also important. One of the losses in the production process is the changeover time related to switching between product types. Production scheduling can reduce the number and time of changeover and setup activities if the schedule is near to the optimal product sequence. As a result of changing customer needs, flexible production structures come to the fore, where production process involves the manufacturing of different product types at the same time. In additional, the unique process plan is given for each product type and they can differ in number or in type of operations. Each operation is linked to a machine or a group of equivalent machines where the necessary operations can be performed.

As a result of the application of Industry 4.0 technologies, individual devices can operate autonomously and communicate to each other on the network. As both the machines and the workpieces are identified, each machine can send messages to the next machine in the process flow to get prepared for the workpiece and reduce changeover time. Due to the different product types moves in the system at the same time, complex material flow relations are created. Fig. 1 illustrates the "job shop" problem in the form of a directed graph for 4 products and 5 machines as an example. Table 1 shows the unique sequence of operations for the product types.

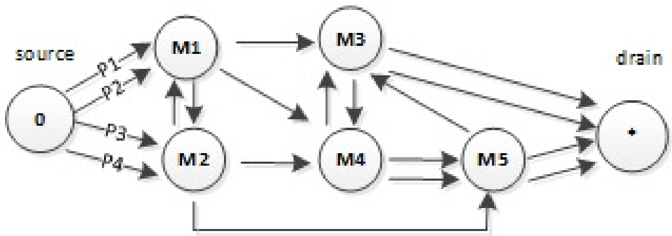

Figure 1. Job shop production model

Table 1. Order of operations by product type

	M1	**M2**	**M3**	**M4**	**M5**
P1	O_2,t_1	O_2,t_2		O_3,t_3	O_4,t_4
P2	O_1,t_5	O_3,t_6		O_2,t_7	
P3	O_2,t_7	O_1,t_8	O_3,t_8		
P4		O_1,t_8	O_3,t_9	O_4,t_{10}	O_2,t_{11};O_4,t_{12}

Each operation (O_i) has a processing time (t_j) that is required for a given operation of a given product type on a given machine.

2.2. Human resources

Several material flow relations exist for each machine as indicated on Fig. 1 Instead of using costly automated material handling, this task is performed by human labor: skilled workers select the next workpiece from the input buffer (source) and move the workpiece between the individual assembly stations (machines) according to the specified order of operations of the product type. The operations are performed at the stations. One worker at a time can perform one operation on a suitable assembly station; thus, if an assembly station is busy, the worker waits until it is released. After finishing the last operation, the assembled product is placed in the finished product container (drain). The cycle then starts again.

Consequently, the workers implement the "one-piece" material flow in the investigated system. The assembly process on workstations cannot be interrupted: workers take breaks only after the product has been placed in the finished product container (at the end of the running cycle). However, the many advantages of using human resources, the negative effects also appear in the production processes: the fulfilment of shift-level / daily / weekly production plans depends on the stochastic effects in the system, which stem mostly from the uniqueness of people. Each operation has a predefined norm time that serves as the basis for the preparation of production plans. From these plans shift-level production plans are generated, typically evenly distributed over the shifts for a given period. Although workers are expected to adhere to the standard time, some differences can be discovered due to the worker's manufacturing and assembly skills. While a rookie is usually not able to adhere to the norm times, more experienced ones perform the operations within the norm time. There may also be differences between those working night and day shifts. Thus, working skills can be interpreted as a percentage of the norm time (average time) of performing a given operation. The complexity of the production process further increased with the involvement of working skills, which also affects production planning, scheduling models and algorithms. This complexity justifies the use of simulation models and methods, with which the indicators of the productivity and efficiency can be evaluated depending on the different production plans and employee skills.

3. Digital model of the production system

3.1. Model objects

A new digital model had been developed before the examination of the presented production system. Real production and logistics processes are mapped in the model as follows:

- Modelling of production equipment (workstations, machines): There are 50 production equipment (A1-A50) with a fixed location in the production system. The cooperation of the production equipment and the worker results in the elementary operation of the manufacturing process on the workpiece, where an essential property of the workpiece changes. A controlled series of property changes make up the manufacturing process, which transforms the workpiece from the initial state to the finished state. The most important parameter of the operation is the processing time depending on the skills of the worker, which can be derived from the standard time for the execution of a specified operation of a fixed product on a given workstation (machine) (1).

$$t = t_{p_{ik}}^{A_j} + t_{p_{ik}}^{A_j}(1 - B_{p_{ik}}^{Operator_l}/100) \tag{3.1}$$

  where:
  - A_j: a j machine;
  - p_{ik}: operation k of product type i;

  - $t_{p_{ik}}^{A_j}$: standard time of operation k of product type i on machine A_j;
  - Operator_l: operator l;
  - B: production skill of operator;
  - $B_{p_{ik}}^{Operator_l}$: describes skills in percent of standard time of operation k of product type:
    - If the operator can maintain 100% of the norm time for the given operation, then the operation time of the operation is the same as the norm time.
    - If the operator is less than 100% able to meet the norm time of the given operation, the operation time increases as the operator works slower, so the time of the operation will be longer than the norm time.
    - If the operator can carry out the operation shorter than the norm time of the given operation (more than 100%), the operation time of will be shorter than the norm time.
- Employee modelling: Workers travel between workstations (machines) on a predefined route at a specified average speed. The worker selects the workpiece on the input storage object ("Start") and then visits the workstations one by one according to the sequence of operations associated with the product type. After the last operation, the finished product is placed on the finished product storage object ("End"). Employees have breaks of predetermined lengths, which they use on decision. Breaks can used only after the finished product has been delivered. As multiple operators work at the same time, queues can form in case of shared access workstations. The operator remains at the station until the current operation is performed. The processing time depends on the actual operator capabilities. Operations are non-interruptible processes. There are equivalent machines that form a group with the same properties (certain operations can be performed on all equivalent machines). In the model, 23 operators (Operator1, ..., Operator23) were implemented for the simulated production environment, with different (very, medium, less efficient) capabilities.
- Product modelling: There are 15 product families and 100 product types in the model. Operation sequences are predefined for product families. The number and order of operations performed on the product types are the same as on product families as types are specialized representation of families. However, norm time of operations may be individually defined.

- ”Start” object (source): Functions as an input container, it stores the workpieces awaiting production, from which the operator chooses one.
- ”End” object (drain): An object that implements the storage of finished products. The finished product is placed here by the operators.

The Plant Simulation model of the production system is shown in Fig. 2 along with the production equipment, workers, and product types currently manufactured. Workers travel on a dedicated route. Paths appear where there is material flow between two workstations. Sankey diagram for two product types is also shown as an example. The thickness of the lines illustrates the size of the volume produced from the product types and indicates the workstations belonging to the technological process of the product type. Large amount of basic data is required for the operation of the model and the examination of the processes in the system, which is stored in a structured form in an external database. In addition to the properties of the basic objects of the model (products, machines, workers), the basic data also include the material flow relations and logical relationships between them. During the implementation of the model, following the previously developed concept model [4], quick adaption of the structure by modifying the basic data is possible. The structure of the model changes automatically, according to the modified basic data. Workstations, workers, products are created or deleted, the properties and data members of the model objects are dynamically updated.

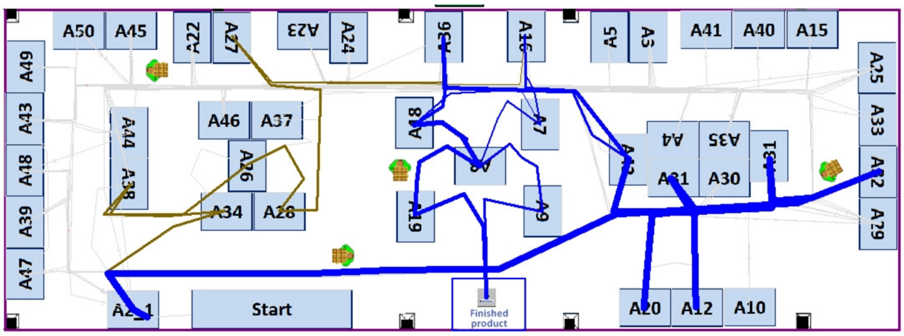

Figure 2. Simulation model

The following consistent data and data structures are required for the operation of the outlined dynamic behaviour digital model:

- Lists of employees are assigned to the shifts. This data structure represents an individual shift schedule of employees.
- List of product families, product types.

- Shift schedule: Cyclic change of 8-hour or 12-hour shifts in daily frequency. In a given shift, a given team of workers with different abilities is available.
- Sequence of production operations of product families, assigning operations to workstations where the given operation can be performed.
- Standard (norm) time for product type operations, which represents the expected operation time.
- Matrix of standard time per operation of product types and capabilities of operators: an element of the matrix shows the percentage of the given operator's ability to comply with the operation time (norm time) of the specific operation.
- Average capability matrix of operators for each product family: an element of the matrix specifies the percentage by which an operator can keep norm time of any operation belonging to a given product family.
- List of production plans:
  - Number of products per product type to be produced during the period.
  - Number of products per product type in shifts to be produced during the period.

The efficiency of the production process and the fulfilment of the production plan are greatly influenced by the order and number of different types of shifts in the examined period, as well as the workers and their production capabilities assigned to shifts.

3.2. Simulation study of the production system

The purpose of our simulation study is to analyse the efficiency and performance of the production system under changing conditions. The first step in the test is to set the current value of input parameters of the model. Currently, two main input parameter sets can be specified:

- The period under review, which defines the order and number of shifts, the operators working in each shift type and their capabilities.
- Production plan for the period considered. This is possible in two ways:
  - The quantity to be produced refers to the entire period under investigation, from which the production plans for each shift are automatically generated by distributing the products evenly depending on the number of shifts.
  - The quantity to be produced can also be specified directly per shift.

Based on the simulation results, statements are made on the performance of the production system, the utilization of the employees, and the number of products produced. One of the most important aspects is the fulfilment of the production plan, therefore one of the main indicators is the number of products produced. The other indicator is the free capacity of the production system over time. The following conclusions can be drawn from the relationship between these two indicators:

1. If the production plan is not fulfilled (there are unmanufactured pieces) and there is significant free time left, then not all batches were manufactured in some shifts due to the workers production capabilities or inadequate management decisions.
2. If the production plan is not fulfilled (there are unmanufactured pieces) and there is no significant free time left, then the production plan is over-planned, i.e., the planned quantity cannot be produced in a given period.
3. If the production plan is fulfilled and there is significant free time left, then the production is under-planned; there are free worker capacities and further pieces can be produced.
4. If the production plan is fulfilled and there is no significant free time left, the production plan adequately loads the system resources and the distribution of workloads is close to the optimum.

However, not only the distribution of the workloads by shift influences the performance of the system and the number of products produced. The management and decision-making strategy that determines the operation of the employees also plays a crucial role. Two events have been implemented in the model that affect employee activity and production system performance:

1. Assigning the product types to be manufactured and the operators to the "Start" object, where the product types to be manufactured in a shift form a queue. The operator selects one of the waiting workpieces in the queue. As there are product families that he is unable to produce at all due to his skills, the operator's default selection strategy is to select the first workpiece from the queue that he can produce. Despite this is a very simple binding, it can have several effects on the production process. The production system is highly sensitive for the order of the production queue. If the jobs behind each other belong to the same product family and the workers can produce them, then the workers follow the same technological path, visiting the same workstations in a row. This may result worker queues at workstations, increasing turnaround time and reducing efficiency.
2. Choice between equivalent machines: in certain cases (such as finishing operations), more than one machine is usable to perform the same type of operation. In such cases, the workers decision strategy is based on a

penalty function, calculated for the available machines. This function also considers the number of products produced.

Simulation studies proved that productivity of the examined production system and adequate utilisation of resources depend on the sequence of jobs in the queue due to the binding of the workers and the workpieces to be produced, in addition to the many influencing parameters and decision strategies.

3.3. Simulation results

The simulation model is suitable for examining the fulfilment of the production plan. The study covers 7 days with 14 shifts, where one shift is 12 hours length. The assignment of workers to shifts and their abilities were predefined. The input parameters of the model are as follows:

- Production plan for the period is indicated in Table 2:

Table 2. Production plan

Product type	**Quantity [pcs]**
_1607	910
_0601	140
_159A	238
_1626	420
_06A8	126
_15A7	70
_1257	714

- Time period of the study, sequence of shifts. The production plan is evenly distributed among the shifts based on the number of shifts (with rounding).
- Type and usage of employee skills:
  - using theoretical operator skills: disregarding the production capabilities of the operators, each operator can produce each product type within 100% of standard time.
  - using average operator skills: the operating time can be calculated from the norm time and the average ability of the worker.
- KPIs in the system:
  - number of products produced
  - remaining free production capacity in time (remaining time is the sum of the remaining times at the end of the shifts when new products are not produced).

Results for the two investigated scenarios (theoretical and average operator skills) are summarized in Table 3.

Table 3. Comparison of simulation run results

	Theoretical skills	**Average skills**
Planned quantity [pcs]	2618	2618
Produced quantity[pcs]	2562	2525
Remaining time [min]	835	339

Table 3 indicates that the produced quantity is less than the planned quantity even if the workers perform with the maximum theoretical production performance. If the simulation runs with average capabilities, the amount produced is decreased because workers are unable to perform operations during norm time. Although this increases the turnaround time of the products, the system has time reserves in both cases. In some cases, the production plan for a shift was fulfilled before the end of the shift. Operators are waiting until the end of the shift in such cases. The time reserve of a shift is defined as the amount of time remaining (free production capacity in time): the difference in the useable time of the shift and the time required to complete the production plan. Analysing quantities produced per shifts (Fig. 3) and free capacities in time (Fig. 4) show that some shifts are overloaded (4, 6, 11, 13), its workers are unable to meet the requirements in the production plan.

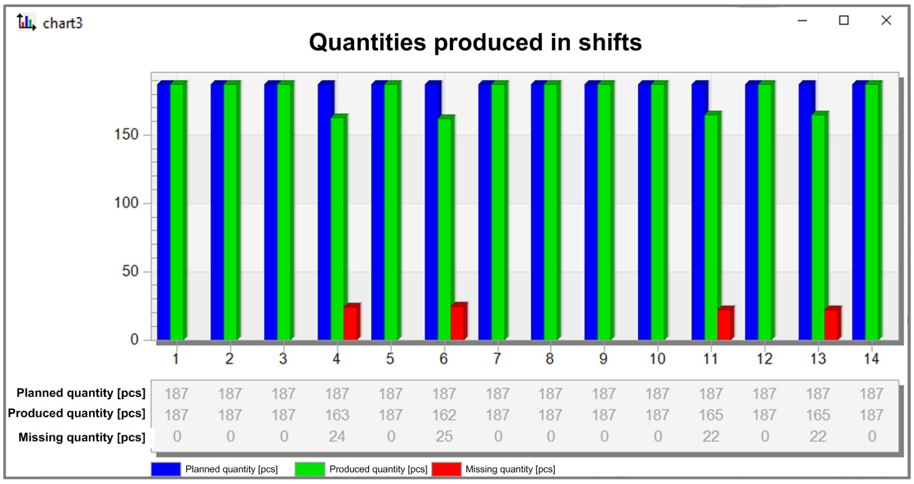

Figure 3. Quantities produced in shifts

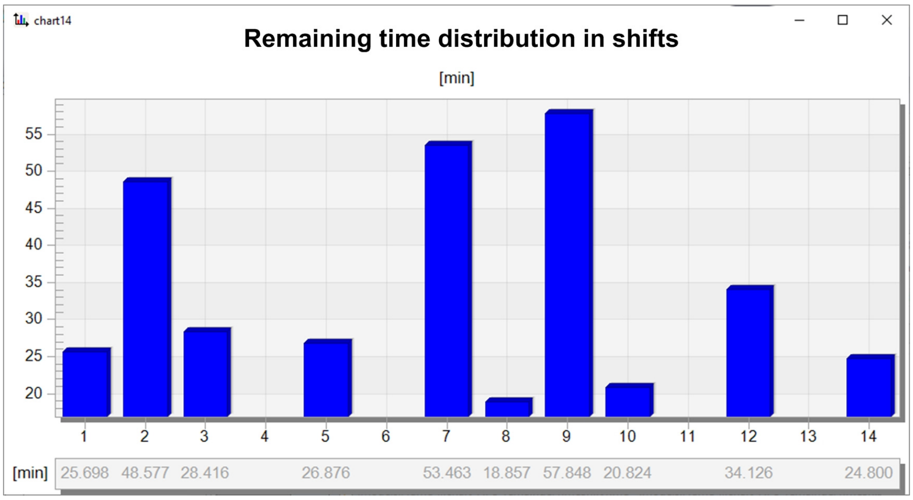

Figure 4. Remaining time distribution in shifts

4. The new heuristic method of the developed Production Plan Optimization (PPO) module

Based on Fig. 3 and Fig. 4 a production plan optimization (PPO) module was developed and implemented in Plant Simulation environment to increase the number of products produced. This PPO module creates an initial production plan based on an even distribution of the products to be produced in shifts. After simulation of the initial solution, an iterative re-planning phase starts. A new heuristic load-balancing method assigns the unmanufactured products to suitable shifts, in which there is available free production capacity (remaining time) and the active employees can perform the additional loads.

The aim of PPO is to achieve an improved production plan that results excellent performance indicators by modifying the evenly distributed loads of shifts and taking employee skills into account. The highly simplified algorithm of the PPO module is shown in Fig. 5 In the preparatory (iteration 0) step, the module evenly distributes the specified production plan among all shifts. Then it runs the simulation and evaluates the performance indicators. If there are unmanufactured products, these are assigned to the first suitable shift in which there is free production capacity (remaining time) and workers can produce these product types.

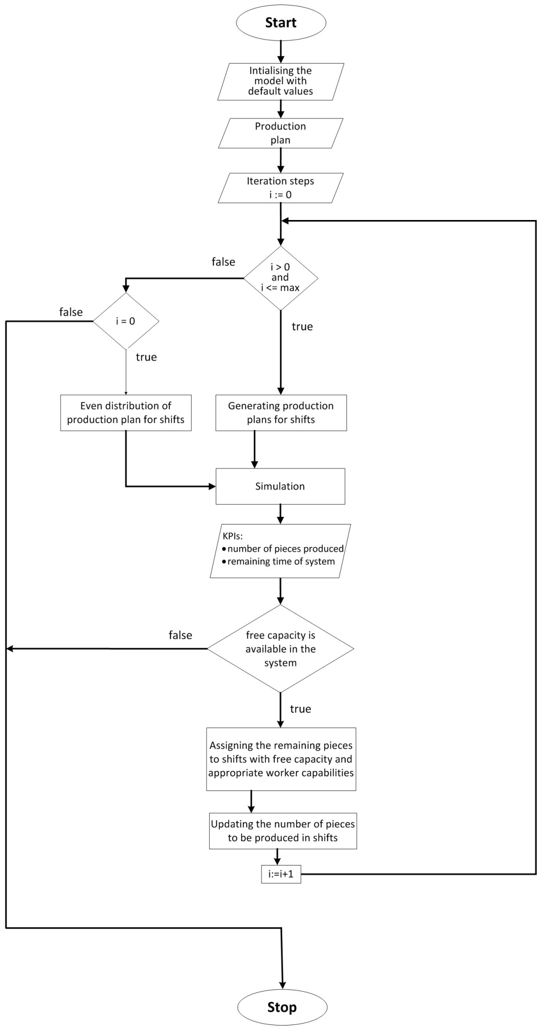

Figure 5. Flowchart of the iterative search algorithm of PPO module

The simulation is run again with the modified production plans, and the performance indicators are evaluated. This iterative process is repeated if there are unmanufactured products and there is free production capacity (remaining time) in the production system, or the number of iterations reached the maximum value. The algorithm can improve the system's performance even with a small number of iterations (Fig. 6). The number of pieces produced increased from 2,525 to 2,609, which indicates the better use of available time base of the production system. This is also shown by the decrease in the free time capacity of the system: from 393 minutes to 85 minutes.

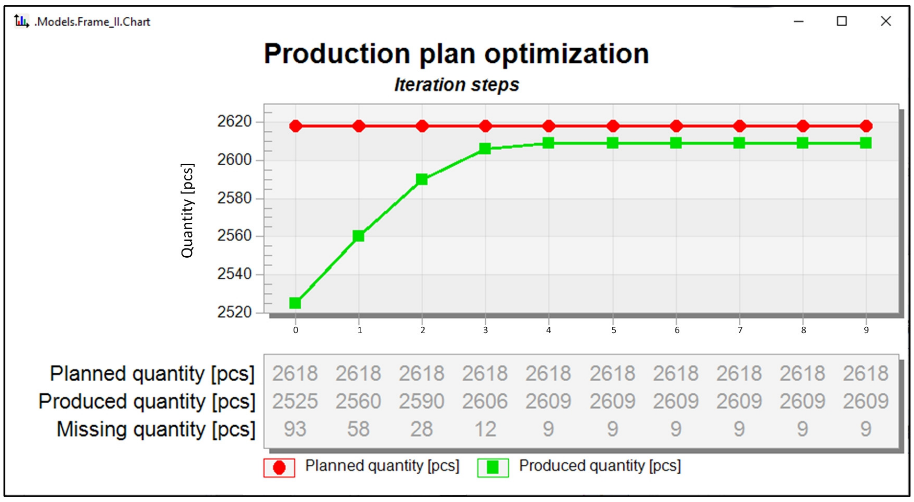

Figure 6. PPO module iteration steps

The result of the iterative improving (re-planning) algorithm is a detailed production plan that specifies the numbers of pieces of the product types to be produced in each shift. As an illustrative example for the investigated case study, the detailed production plan is indicated in Table 4.

Table 4. Number of pieces produced in shifts

Shift types	**1.A**	**2.B**	**3.D**	**4.C**	**5.D**	**6.C**	**7.B**	**8.A**	**9.B**	**10.A**	**11.C**	**12.D**	**13.C**	**14.D**
_1607	69	68	67	56	68	56	70	68	70	66	57	68	56	71
_0601	10	11	11	9	10	9	10	10	11	10	9	11	9	10
_159A	18	19	17	15	18	15	18	17	18	18	15	17	15	18
_1626	30	33	32	26	31	27	32	30	32	31	27	30	27	32
_06A8	9	10	10	8	9	8	10	9	9	9	8	10	8	9
_15A7	6	5	5	4	5	4	6	6	5	5	4	5	4	6
_1257	53	54	53	44	54	43	55	54	55	52	43	54	44	56
Even distribution	187	187	187	187	187	187	187	187	187	187	187	187	187	187
PPO module	195	200	195	162	195	162	201	194	200	191	163	195	163	202

The implemented heuristic algorithm reduced the number of pieces to be produced in some shifts, while it was increased in other shifts. Type C shift workers appeared in the system as bottlenecks. Their low production capability worsened the productivity of the shift.

5. Summary and further development

In this paper, a special model of a flexible production system was presented, where human resources, production efficiency and employee skills play key roles to achieve the maximum productivity that can be expected from the production system. This direction of modelling and development is necessary because the human factor also has a strong influence on the performance of the flexible production process. In conclusion, the human factor must be integrated into the models and methods of organization, planning and scheduling of production to achieve the desired effect of the planned changes that aimed to increase the efficiency.

For this purpose, a digital simulation model was developed, which is suitable for considering the impact of the human factor at the levels of production planning, scheduling and control. A new heuristic algorithm was used, which increases the performance of the production system by improving the production plan for each shift. Even better results may be reached with optimizing the production sequence by using a novel strategy to assign dynamically the workpieces to the workers. This strategy can be put into practice if the control system supports each worker to select the workpiece that best suits his production ability and takes the product types already in production into account to reduce waiting times at workstations. This concept can be ensured by maximizing the heterogeneity of the product types produced at same time. It is recommended that the worker should choose a product type that few workers can produce. It is preferred that the control system also considers the production capability of all the other workers in order to effectively manage the dynamic manufacturing processes.

This proposed approach ensures the continuous work of the workers and increases the number of pieces produced.

In the future, several additional considerations must be taken in order to determine automatically quasi-optimal shift-level production sequences. We are developing a multi-objective priority-based rescheduling algorithm to extend the presented simulation model and solutions.

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