New approaches in production scheduling using dynamic simulation

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Abstract. The Industry 4.0 is current phenomenon in industrial enterprises, which brings a revolutionary way of production. As Industry 4.0 is applied to the entire lifecycle and value chain of products, its success depends solely on the flow of information across the system. That's the point where we get the benefits from a dynamic simulation solution which is one of the cornerstones of future businesses. The solution from Siemens Tecnomatix, the Plant Simulation module, provides an effective tool for planning and scheduling manufacturing processes. This article deals with the scheduling integration of production and simulation from the field of planning and production management at the workshop level. At the same time, it focuses on the problem of custom-made production and describes the possibilities of using simulation as a new production scheduling approach.

1. Introduction
At present, management and scheduling of production is focused mainly on one-piece and low-volume production, which makes 60–70% of the total production volume in business with a wide-range production program and large number of parallel orders. This is a current issue in industry, which is also confirmed by the broad cooperation development between industry and tools of digital factory in manufacturing processes and systems [4].

The main purpose of the production planning is to meet market requirements while minimizing costs associated with production, storage and unfulfilled orders. That requires, the output of the production process to be as accurate as possible to meet the requirements, while respecting all constraints that exist in production processes and systems – Figure 1. The outcome of the production process can be influenced in a way, how the production orders are placed into production, which production facilities are involved in product manufacturing and what quantity of work in progress exists in these processes [5].

2. Difference between production planning and production scheduling
Planning is what allows to put the best plans for the necessary tasks into action. Planning and scheduling are interdependent and require full understanding of all the variable parts of the selected production system. In theory and practice, there is a clear distinction between planning and scheduling.

Planning is a high-level process in which it is necessary to determine what work to be done and what materials are needed to carry out this work. It includes a strategy of what to be produced on each
machine during each production period. Planning is usually done in the context of time periods (e.g. weeks or months) and it can be determined without a detailed model of the company.

Scheduling, on the other hand, will transform this top-level plan into a detailed and reliable short-term production schedule. So it is possible to produce the required parts and meet the key objectives, including delivering parts in time. Scheduling focuses on intensive short-term discussion regarding production resources, materials and requires that all critical variables and constraints in the production system are fully understood [7].

Scheduling provides the greatest advantage when one or more of the following conditions are present:
- In custom-made production, where orders are created to meet the demand for a specific customer’s product, rather than a simple market situation,
- In a more complex Make-to-Stock model, which produces a number of products with significant changes, what leads to manufacturing sequences that significantly affect the throughput of the production,
- When delivery of the product to customers in time is a key performance indicator,
- If there are multiple products produced at the same time and each product flows through the system differently and
- Unplanned, but probable failures - such as machine failures or late arrival of materials - require a schedule [3].

Scheduling does not provide an advantage in a relatively simple direct production of a single product (most assembly lines), as such items are manufactured continuously.

Figure 1. Information flow in production system (Pinedo, 2016).
3. Production scheduling

Production scheduling is a process in which we determine the order of production tasks and operations to make the most efficient utilization of production resources. [6]

According to Gregor (2005), scheduling of production operations is defined as "the problem of balancing production requirements and available production capacities." It also highlights the fact that maintaining a balance between production requirements and available production capacities is the daily role of managers who decide on the dynamic allocation of production orders, the efficient use of resources and the delivery dates fulfillment. Such decisions are complicated and affect the final business efficiency. [12]

The main targets of scheduling include:
- Fulfillment of production order deadlines,
- maximum utilization of production resources,
- minimal Work in Progress (WIP),
- minimal production lead time.

To accomplish these targets, key tasks need to be met:
- Assignment of operations which to be performed on particular products by the production facilities, eventually to create task queues on workstations with specific devices. The assignment should be done as efficiently as possible so that the workloads of the workplaces are balanced. This step only generates a rough plan, using the average waiting and transport times.
- To determine processing order (sequence) in order to achieve a minimum production lead time with maximal utilization of the device production capacities. In this step, there is prepared precise short-term production schedule with consideration of all interactions of individual products, specific downtimes, etc. [5].

4. Basic production scheduling problems

Each scheduling task must have defined basic parameters, which include the characteristics of the machines and the operations that need to be scheduled on these machines. Apart from these basic characteristics, some other attributes are often present, in particular the different types of boundaries or the definition of the resources consumed by the tasks.

There are two basic types of machines in terms of scheduling:
- Parallel - the task runs on any machine.
- Dedicated - a task can only run on a specially designated machine.

4.1. Scheduling of parallel machines

In case that any of the available machines can be used to solve individual tasks, we talk about tasks scheduling on parallel machines. In this category of tasks we distinguish two basic cases, single stage production if only one machine is available. The second group consists of the so-called multi-stage production when multiple machines are available for scheduling. [6]

4.2. Scheduling of the dedicated machines

If only specialized (dedicated) machines can be used to solve individual tasks, we talk about scheduling tasks on dedicated machines. In this case, tasks are used to being divided into groups, so-called orders, in which individual tasks being carried out on different specialized machines in a single order. From the prescribed sequence and the number of operations then depends, which of the four main types of tasks on the dedicated machines is present. Main types of scheduling on dedicated machines:
- FSSP (Flow Shop Scheduling Problem)
- JSSP (Job Shop Scheduling Problem)
- OSSP (Open Shop Scheduling Problem)
- MSSP (Mixed Shop Scheduling Problem)
4.2.1. Flow Shop Scheduling Problem FSSP
For this type of scheduling issue, operations are performed in all tasks in the same order. Consequently, tasks must follow the same route (Figure 2a). Machines are supposed to be arranged in series and their surroundings are referred to as a continuous flow.

The general mechanical engineering environment consists of several phases with a series of machines parallelly in each phase. The task must be processed in each phase on only one of the machines, and such an environment is called a flexible continuous flow (FFSSP), as shown in Figure 2b. Flexible continuous flow is a generalization of continuous flow (FSSP) and parallel arrangement of machines.

![Figure 2. Flow shop scheduling problem.](image)

4.2.2. Sequential problem JSSP
Expanding the Current Problem (FSSP) has created a classical sequential problem (Figure 3a), which is considered the biggest problem within the production scheduling. In a classic sequential problem, each task has a predetermined own run, and each task must be processed on available machines, while the performed operations can attend the same machine only once due to consideration with the same amount of operations and machines.[3]

In the productions with technological arrangements was created a modification of the current problem with the parallel arrangement of identical machines, which is called Flexible Job Shop Scheduling Problem (FJSSP) (Figure 3b). In this problem, it is necessary to specify the addition of an operation to a specific machine over a classical sequential problem.

![Figure 3. Sequential problem JSSP.](image)

4.2.3. Open Shop Scheduling Problem OSSP
The Open Problem (OSSP) (Figure 4) is a special type of scheduling problem that is different from the classic scheduling problem in that the sequence of operations is not predefined, and in some cases the processing time is zero. Typical cases of open scheduling problems are small and medium-sized enterprises focused on service activities.
4.2.4. **Mixed Shop Scheduling Problem MSSP**

The goal of a mixed problem (MSSP) is to break down tasks whose part has a predefined flow through the production system, and the part is allocated without limitation to the order of the scheduled operations. Examples are operations that correspond to the technological arrangement of the production facilities in the first part of the production and subsequently are assembled. The presumption is that the mixed scheduling problem is a combination of a sequential and open problem of production tasks scheduling.

5. **Overview of current approaches to solve examined problematics**

Due to the wide variety of aspects and features that may occur in production systems, it is not surprising that a large number of different scheduling models can be found in the literature. This chapter provides an overview of methods and methodologies applied to solve problems in production scheduling.

5.1. **Mathematical programming**

Mathematical programming is one of the most widespread methods of operative research and management science. Its application has been successful in many cases and its usage has gradually moved beyond the research departments where it has become a common practice in planning. The common feature of these models is that they all include optimization. Parameters which are subject to maximize or minimize are referred to as objective functions. Mathematical programming models have been and are also widely used for scheduling problems.

The most common mathematical programming models used in production scheduling are:

- Linear Programming (LP)
- Integer Programming (IP)
- Mixed Linear Programming (MIP) [9]

5.2. **Constraint Programming (CP)**

Unlike mathematical programming which has its roots in operational research, constraint programming is a relatively young discipline that has its origins in artificial intelligence, and in recent years has often been implemented in combination with operational research to improve its efficiency. Constraint programming has already been in the literature since 1970. Abhishek (2010) states that it is still not as widely applied as mathematical programming, but has already achieved some of its successes in planning and related areas. Constraint Programming (CP) formulates the problem by defining the limitations, but unlike the mixed integer programming (MIP) solution, it requires searching for a feasible solution that meets that limits. Hooker (2012) states that the constraint programming method was developed primarily as a tool for finding solutions that are sometimes less effective in minimizing costs. [7, 12]
5.3. Heuristic methods
The use of complete exact methods to solve complex combinatorial optimization problems often leads only to theoretical calculations. This phenomenon led the vast majority of researchers from such problems to methods of approximation. Approximate methods guarantee finding of the optimal solution in order to obtain an optimal solution in a reasonable and practical calculation time. The basic form of algorithm approximation is called "heuristics", a name derived from the Greek verb "heúrēka", what literally means "I have found". The usual classification of heuristic methods is:
- Constructive searching methods
- Local searching methods[4]

5.4. Meta-heuristic Methods
These meta-heuristic methods have an advantage over heuristics when it comes to more robust solutions. They are more challenging to implement and align. The purpose of meta-heuristic methods is to efficiently and effectively investigate the searching of space driven by logical transitions and knowledge of their impact. Meta-heuristic algorithms can be divided into:
- Population-based methods - they generate new solutions that share the benefits of original solutions, and newer results are expected to deliver even better results.
- One-Point Searching Methods - refine solutions based on specifics as a result of searching for neighbors with set shifts.[9]

6. Scheduling rules
In order to determine the processing sequence, it is first necessary to determine the so-called rule of order, i.e. the selection decision rule, according to which the products will be selected from the work queue and assigned to the workplaces. In the case that given operation can be performed by multiple machines, another problem is also to determine the selection rule for machine selection (machine queue) which performs the operation. As can be seen, in a large number of tasks with many operations and a larger number of machines, a huge number of combinations of possible solutions emerge. In some complex cases, heuristic approaches are used, or the solver must just use his common sense.[12] Some of the basic rules used for scheduling (product selection determining the appropriate processing sequence):
- Random select (RS)
- Shortest Processing Time (SPT)
- Weighted Shortest Processing Time (WSPT - Weighted SPT)
- Earliest Due Date (EDD)
- Minimum Planned Start Date (MPSD)
- Minimum Slack Time Per Operation (MSTPO)
- Newest part (NP)
- Oldest part (OP)
- Low Part Priority (LPP)
- High Part Priority (HPP)

When choosing a device from several available devices, it can be:
- Low usage station
- High usage station
- Station with fewest processed parts
- Station with most processed parts
- Low station priority
- High station priority
- Min setup time
- Max setup time etc.

Production management often uses priorities, so to each individual production task is assigned the different "speed" how fast it should pass through production and at the same time open to it "traffic
lights” for a smooth pass through production. There are used more approaches to decide which product will be of higher priority in the following periods. One of the classic approaches is the calculation of the so-called critical ratio.

\[
CR = \frac{\text{Remaining time for finishing}}{\text{Remaining time for processing}}
\]  

The next selected product for processing is that with a minimum CR value. As seen, CR represents actually the ratio of demand time and delivery time.

If CR>1, then it is enough time to finish the product

If CR<1, then the product will be delayed if there is no action with its processing time.

CR = 2 means, that there is twice as much time to finish the product than the remaining time of its completion [8]

7. Simulation

The simulation allows to simulate every manufacturing system and through its dynamically changing processes included in the model we are able to simulate different variants of experiments to get knowledge transferable to the real production system. In discrete simulation, the parameters of the individual components are changed by simulation control. These events are carried out gradually - discreetly. Thanks to these simulation features, it is possible to perform a dynamic system monitoring where it is possible to monitor the behavior of individual sources within the specified time period, as opposed to static calculations. A suitably designed simulation model provides a number of essential information, which enable the corrective actions in the created production plan to be implemented [10].

7.1. Application possibilities of simulation in production scheduling

Production scheduling and simulation are a long-term and especially efficient techniques. These two techniques belong to the field of operational research and both techniques have complementary strengths, which are coming from basic definitions.

Scheduling using simulation is used to solve complex problems that cannot be solved by analytical methods, because the analytical description itself is impossible. In scheduling tasks, the goal is mainly to find a sequence of operations on available machines so that all operations from the tasks are processed in the shortest possible time [2].

7.2. Production scheduling in software environment of tecnomatix plant simulation

Simulation-based scheduling depends on the assembled simulation model that provides the basic constraints model of the manufacturing system. The simulation model captures all resources (including elements such as devices, tools, and staff) as well as materials that are consumed and transformed within the production process. The quality of the final production schedule is managed by heuristic decision-making rules that are incorporated into the model. Software environment of Tecnomatix Plant Simulation offers a module for production scheduling. The simulation model represents a real multi-product manufacturing system, capturing all its influential factors. There are fixed production system structure and production procedures in the model. Factors are e.g. operating and set-up times on individual production device, material flows, failure rate, product processing priority, and others that depend on the specific product type. In the assembled simulation model, there are no fixed variables, but they vary depending on the product types passing through the production system in the current time interval.[1]

The dialog box of simulation system serves as a control menu for the scheduling model. This menu is divided into 3 main sections. The part of the input data, in which it is set the monitored period of the schedule, the production facilities as well as the production plan. The second part triggers time control in the simulation model. The third part contains output data that shows the number of produced pieces in the selected period (shifts, days, weeks). It is also possible to display the production plan for the
selected time period. The HTML button provides an output report of the results according to the preset metrics we want to track.[11]

7.2.1. Production Schedule Obtained by Simulation
The simulation of production scheduling provides a comprehensive overview based on selected priorities, according to which it is possible to define what product is to be produced in what quantity and at what time. At this stage, an accurate short-term timetable is already in place, considering all the interactions of the individual products and the precise production and set-up times of the individual production devices.

![Schedule model in tecnomatix plant simulation.](image)

Figure 5. Schedule model in tecnomatix plant simulation.

| string | integer 1 | integer 2 | integer 3 | integer 4 | integer 5 | integer 6 | integer 7 | integer 8 | integer 9 | integer 10 |
|--------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1 F-208098-0011.IR.RNN | 1KW | 5238 |
| 2 F-208098-0011.IR.RNN | 2KW | 5238 |
| 3 F-218917-0111.IR | 3KW | 4008 |
| 4 F-218867-0011.IR.RNN | 4KW | 4008 |
| 5 F-218974-0011.IR.RNN | 5KW | 4250 |
| 6 F-213617-0011.IR.RNN | 6KW | 400 |
| 7 F-212534-0011.IR.RNN | 7KW | 4650 |
| 8 F-204782-0011.IR.RNN | 8KW | 4650 |
| 9 F-217411-0111.IR | 9KW | 5947 |
| 10 F-217411-0011.IR | 10KW | 6520 |
| 11 F-230698-0011.IR.RNN | 11KW | 6075 |
| 12 F-218299-0101.IR.RNN | 12KW | 4500 |
| 13 F-553337-010011.IR.RNN | 13KW | 4500 |
| 14 F-559270-0011.IR.RNN | 14KW | 5040 |
| 15 F-559270-0011.IR.RNN | 15KW | 5040 |
| 16 F-559270-0011.IR.RNN | 16KW | 5040 |
| 17 F-204782-01-3001.IR.RNN | 17KW | 5508 |

Figure 6. Schedule plan for week.

These priorities can be varied on the basis of searching for an optimal solution of the production plan, equipment utilization, etc. The result is a schedule in form of diagram (Figure 7). The obtained production schedule includes the weekly plan of the produced components and their quantities during the reference period [5].

Subsequently, there is provided report with the ratio of requested quantities during a given period to the number of pieces actually produced during the reference period. Such an overview of the individual periods gives us a clear answer, if the chosen approach for production scheduling with use of simulation is possible to accept and follow it or it is necessary to take corrective action to ensure the fulfillment of required outputs from the production system.
The assembled experiment clearly points to unfulfilled market demands (backlog). In this case, the simulation experiment is restarted. Using the control menu, a different approach to production scheduling is selected, which results in the change in the behavior of the entire production system. By changing the approach, new results will be obtained that will allow us to approximate not only the situation in the production system, but also which of the proposed plans is to be adopted in order to prevent sanctions as a result of the delayed final product, unfulfilled quantities of final products etc [3,10].

8. Conclusion

Even the best software for scheduling program, using classic scheduling approaches, cannot ensure the design of an optimal short-term plan. The reason is the fact that each of these programs use in scheduling a constant value of the activity duration. In reality, however, the times of operation and the times of waiting and interruption are not constant, but the lengths of their duration are random variables. Any scheduling system is not able to take into consideration accidental malfunctions in the production and their impact on the final short-term production schedule, which does not allow in advance verifying the "robustness" of the proposed plan using sensitivity analysis.

Until now, the only known tool which allows "testing" of the proposed short-term production plan with respect to these facts is a discreet computer simulation. By using individual production scheduling modules, it is possible to examine production systems, detect waste sources, assess the generated schedules of individual orders, and optimize their performance. We have the opportunity to obtain an objective view of the entire production system and, based on the obtained results, to evaluate the generated schedule according to the key indicators that clearly determine whether it is possible to follow this production schedule during the reference period or it is necessary to further experiment with the schedule. By applying the scheduling module to the problem we investigated, we were able to detect deviations in the production requirements (Fig.7). An important part of the reuse of the model is its updating. The user not only changes the production plan, but needs to constantly update the basic process data in the simulation model (machine failure, cycle times, sort times...). The results obtained with the simulation software can be linked to enterprise information systems that are directly linked to the level of production management and production planning. Thanks to that it is possible to exclude planning based on decision making of individual responsible worker in production, so that we can meet the customer's demand with efficient use of the production capacities of the given production facilities. Ultimately, it will simplify the work of the planner, who has the task to create, evaluate and select production plans in order to achieve the required key indicators.

![Figure 7. Statistics obtained by the tecnomatix plant simulation.](image-url)
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