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Integration of Digital Twin with Simulation in Order to Meet Factory Expectations

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Abstract: This article presents the results of a research project carried out in a factory of an aviation manufacturer of aircraft engine parts. The project aimed to design a simulation model for the company's department producing the factory's critical items with extensive lead time: approximately 50–60 days. The company's engineers validated the model by comparing it against historical and reference data for the modeled line. The real-life sequence was used as a reference for simulation experiments. Two sequences with shorter lead times have been found. Results of the project inspired the company to redefine its approach to management by preparing dynamic production plans adaptable to environment variables. Based on the simulation project, a conceptual method of proceeding was proposed enabling the introduction of such a task. The concept proposed restructuring the factory, defining observation points and integrating the digital twin along with "What-If" simulation experiments. By distinguishing between the location and operation observation points one can map the real life processes onto the simulation model. Consequently, experiments can be launched, simulating possible scenarios starting from a predefined moment of the actual real life process. Also the benefits resulting from the application of the proposed solution were defined.

Key words: digital twin, computer simulation, manufacturing, making decision

I. INTRODUCTION

This article describes the results of a research project, carried out in an aviation industry company that manufactures parts for aircraft engines. The focus of the project was to discover how the production sequence arrangement affects the flow time. The company undergoes digitalization – currently identifying its digital maturity in order to implement Industry 4.0 solutions.

The factory board acknowledge the need to implement Industry 4.0 solutions, meanwhile looking for their unique approach to manufacturing in aviation. Quality measures are of particular importance as they extend the production cycle. The factory board attempt to reorganize the factory to align it with the key Industry 4.0 principles [1]:

- continuous and immediate communication across workstations and tools, integrated with production lines and supply chains, resulting in a digital and flexible factory;
- the use of simulation and data processing tools to collect and analyze data from assembly lines, further used for modeling and testing; this is of great value for the employees trying to better understand industrial circumstances and processes;

- the use of communication networks for continuous and immediate exchange of information aimed at coordinating the needs and availability, which results in resource and energy savings.

In order to gain its own experience (in the past the factory had not used simulation technologies for operational management) a simulation project was initiated. Its goal was to construct a simulation model for the department producing the most important products of the factory for which the so-called lead time was very long: approximately 50–60 days. In the project the process of producing a series of 9 products was mapped in a sequence resembling the real-life sequence. Then, the following question (or research thesis) was formulated: does a change in the production sequence affect the transition time?

The board expected to receive a positive answer to the formulated research question and, on the grounds of this experience, develop a formula for introducing Industry 4.0 solutions in the enterprise.

The project conclusions, literature overview and interviews with company managers resulted in a concept of the factory digital twin using DES/ABS simulation (DES – Discrete Event Simulation, ABS Agent Based Simulation). Thus, the main goal of this article is to present the results of the simulation project and propose a concept for introducing a digital twin solution using DES/ABS simulation.

Herein we present the concept of integrating the factory digital twin with DES/ABS simulation along with the requirements necessary for such integration and expected results. Highlights of this article include

- a definition of requirements for real-time simulation: a definition of decision points and their observation,
- structuring the digital model: identifying the route cycles – separation between the execution and decision levels – the consequent definition of shared points between the real process and the digital twin / simulation model.

Contribution from the authors is the structuring of the simulation model enabling its integration within the digital twin and the concept of a simulation experiment instance for "What-If" type of discovery action research.

This paper is organized as follows. First, the theoretical background of the paper is presented along with the most relevant definitions, including material flow, material handling, simulation and digital twin within the context of Industry 4.0. Then, the research problem is formulated and proposed solution and implementation are described. Finally, the conclusions as well as expectations of the factory are defined.

II. LITERATURE OVERVIEW

The term Industry 4.0 was first used in 2011 at the Hanover Fair in Germany [2]. The German government then presented the Industry 4.0 initiative plan for long-term protection of the competitiveness of the domestic manufacturing industry [3]. Industry 4.0 is defined as a generic term for various digital concepts, such as IoT, CPS, big data, data analytics, digital twin, digital shadow, HRC, etc. [4]. These concepts promise new potential for production planning and control. A smart factory is characterized by interoperability, virtualization, autonomy, real-time operation, customer orientation and modularity. Interoperability means that objects, machines and people must be able to communicate with one another through the Internet of Things and the Internet of People. Everything physical must have its virtual copy – a model (virtualization). Cyberphysical systems are characterized by the ability to work autonomously, which in turn paves the way to mass personalization of products. Moreover, autonomy provides a flexible production environment that facilitates innovation. In a smart factory data is collected in real time, aggregated, analyzed, and decisions are made in accordance with new arrangements [5]. The aforementioned smart factory functions – interoperability, virtualization, autonomy and real-time operation – are currently being implemented by IoT and DT.

IoT is a system of distributed, interconnected and digital identifiers, communicators, sensors and actuators. They are built into objects or worn by humans and animals. They are identifiable and can transfer data over the web without human-human nor human-computer interaction.

The primary function of a production plant is to manufacture products for a specific purpose and following a specific process. The function is performed within the production and logistics system and includes the following main types of logistics activities:

- material flow control – situational and managerial approach – material flow,
- material flow conversion – engineering approach – technology.

Engineering activities aim to define the objects and principles of material flow transformation in the "product – process – resource" system. The digital model of these objects is a static model, construed during equipping and modernizing the company's plant as well as during the technological preparation of production. Operational activities are determined by production plans and work schedules, quantitative material flow rates, resource availability, their capacities and operating parameters in a given period. During operational activities data on the current state of material flow, the state of workplaces, etc. are collected. They create a dynamic, digital data model. Concepts such as (1) static digital model; (2) dynamic digital model are discussed and defined in the literature as digital model, digital shadow or DT. Many authors focus primarily on real-time work and the flow between a real and digital object, introducing the concepts of digital model (manual data flow), digital shadow (manual and automatic data flow) and DT (automatic data flow only) [6].

At present, it is challenging to propose an unambiguous definition of DT [7, 8]. On the one hand, various authors cite the definition of Michael Grieves [9], who is considered to have coined the term DT ("The DT concept [...] consists of three main parts: a) physical products in real space, b) virtual products in virtual space and (c) [bi-directional] connections of data and information that bring virtual and real products together"). On the other hand, authors of various works propose their own definitions, as mentioned for example in [10].

Many authors have discussed the adequacy of DT, arguing that the same company may have multiple DT depending on the requirements [11]. A simple description of an object, such as a drawing or a 3D model of a product, is already its DT in some sense, but has a low level of adequacy. Yet, it is impossible to fully describe any object. The parameters of each object exist in an infinite set. Therefore, the level of adequacy is always limited. However, to solve a specific task you can specify a limited, necessary set of parameters. Collecting data from a real (physical) object, and thus describing only its current state, is not the only purpose of building the DT. This only addresses the concept of the digital object shadow. It is a Big Data set in which relations and dependencies describing the state of the real object are taken into account. A digital shadow stores all readable parameters of an object or system. On the other hand, DT must be able to identify and separate the given content without contamination and noise. It must also include the necessary set of laws and rules describing the behavior of the object and enabling the simulation of its various states. Simulation and optimization play a special role here, since they enable answers to "What-If" questions in various scenarios. Optimization enables us to discover the best parameter settings for achieving a predefined goal function. These are indispensable decision-making tools.

III. DEFINITION OF THE RESEARCH PROBLEM

The research project was carried out in an aviation industry company producing parts for aircraft engines. The manufacturing processes of 9 products were analyzed. Each technological and production route consisted of 30–40 technological operations (the number of operations depended on the type of product). In the processes some operations were performed in internal, while others in external cooperation. Internal cooperation means that the parts were transported in the right container and in the right number to another building (department) of the factory – billing separately. External cooperation means that the parts were transported in the right container and in the right number to an external company cooperating with the parent company on the basis of a cooperation agreement. The said cooperation related to specialized technological operations would extend the time needed for the product to go through the entire process (so-called lead time). There are so-called returns in the process, which means that a part is processed several times by the same machine. In the process the part is repeatedly returned to the same machine for further processing, each time with a different set of parameters, which further complicates the orchestration of the processes. Considerable costs of machines on the one hand and their specificity on the other make it impossible to organize the process in line, from the so-called one piece flow perspective. The full production cycle/process takes 50–60 days. This lead time is the total time needed for a part to go through the full process from entry to exit, including all waiting times. Lead time is one of the most important measures in logistics.

A sample process description (a sequence of technological operations) is provided in Tab. 1. The column descriptors in Tab. 1 stand for: T_{pz} – time used for retooling of the workstations, T_{j} – time used by the workstation to produce a single unit of the product.

External cooperation operations lack defined normative times: instead these are usually specified in the cooperation agreement, which guarantees the performance of operations within the number of days defined by the contract, including the transport operations to and from the cooperator. The following goals were defined for the project:

- to analyze various production plans against the lead time – considering a varying order of introducing products into production,
- to verify if the batch size adopted in the enterprise is optimal (batch size with shortest transition time),
- to verify (introduce) multi-profession – currently an employee is permanently assigned to the machine using a competence/skills matrix of employees,
- to calculate the level of work in progress.

IV. SOLUTION PROPOSAL AND IMPLEMENTATION

During the course of the project it was considered to solve the defined task with analytical and simulation methods. However, due to the complexity and dynamics of the process, it surfaced that it would be very difficult to define a mathematical (analytical) model for such a process, which would additionally take into account changes in the sequence of manufactured products. Additionally, difficulties related with the validation and verification of the results achieved by the enterprise would arise, which would be the case for both the analytic or the simulation model. Therefore, a decision was taken to use a simulation technology: to build a simulation model, validate it, and then perform simulation experiments for various scenarios of the manufactured products' sequence. Consequently, the FlexSim simulation package was used for building the simulation model, although there are many simulation software on the market: Anylogic, Arena, FlexSim, Simio, Tecnomatix Plant Simulation, and Witness. Available simulation software is based on discrete events but also provides the ability to control tasks. The limitation of many software products is that they only provide the two dimensional visualization (2D), which

Tab. 1. An example of a machining process

Op.	Workstation name	Operation short text	T_{pz} [min]	T_{j} [min]	Times sum
0070	CNC lathe	CNC lathing	100.000	26.559	631.18
0100	Slusher and assembly station	Slushing	5.000	1.000	25
0110	Rotary table washer	Washing instr. 35-03	10.000	2.000	50
0120	ext. cooperation	Copper Plating	0.000	0.000	0
0123	ext. cooperation	Copper Plating	0.000	0.000	0
0125	Bench drill (for chamfers)	Lapping Chamfers	10.000	1.800	46
0130	Roll grinder	Grinding	25.000	11.000	245
0145	Hole grinder	Grinding	30.000	4.800	126
0155	Vertical broach	Multi broaching	35.000	3.700	109
0157	CNC tooth soldering iron	Multi soldering	75.000	9.290	260.8
0160	Hobbing machine WMW & LIEBHERR – new	Tooth hobbing	105.000	20.040	505.8
0165	Slusher and assembly station	Slushing	10.000	5.500	120
0175	Rotary table washer with interoperation checks	Washing instr. 35-03	20.000	3.000	100
0195	Carburizing	Carburizing	95.000	12.700	325
0220	ext. Cooperation	Detachment	0.000	0.000	0
0225	Injector cleaner	Cleaning	5.000	1.000	25
0250	ext. Cooperation	Detachment	0.000	0.000	0
0255	Hardening	Hardening	60.000	25.100	562
0275	ext. Cooperation	Detachment	0.000	0.000	0
0280	Polishing and cleaning	Cleaning	65.000	8.600	237
0320	Bench drill (for chamfers)	Lapping chamfers	10.000	6.200	134
0325	CNC roll grinder	CNC grinding	30.000	9.100	212
0335	Center grinder	Grinding	25.000	3.000	85

is not easy to visualize, understand and evaluate or 2D/3D where three dimensional visualization is available as post-processor – only for visualization, not for direct work with 3D objects. The FlexSim software was chosen because it is core 3D (working directly in a 3D environment) and it is an open system, i.e., system logic can easily be defined by using Process Flow, a graphically-based, logic-building tool that is a part of FlexSim [12].

The simulation model was built according to the methodology defined in "Applied Simulation. Modeling and Analysis using Flexsim " [12]. The constructed model consisted of 17 workstations served by 21 employees. Internal and external cooperation operations were represented by the so-called black box, which only reflected the time of execution of these same operations from historical data. Fig. 1 shows the general view for model included internal and external cooperation, and Fig. 2 shows a detailed view for the production process.

Tab. 2. Selected results from performed simulation experiments

Row no.	**Sequence 1**	**Sequence 2**	**Sequence 3**
1	Product_1	Product_9	Product_3
2	Product_2	Product_8	Product_4
3	Product_3	Product_7	Product_2
4	Product_4	Product_6	Product_1
5	Product_5	Product_5	Product_7
6	Product_6	Product_4	Product_8
7	Product_7	Product_3	Product_6
8	Product_8	Product_2	Product_5
9	Product_9	Product_1	Product_9
	53days 08:56:28	**52days 20:15:46**	**52days 04:15:40**

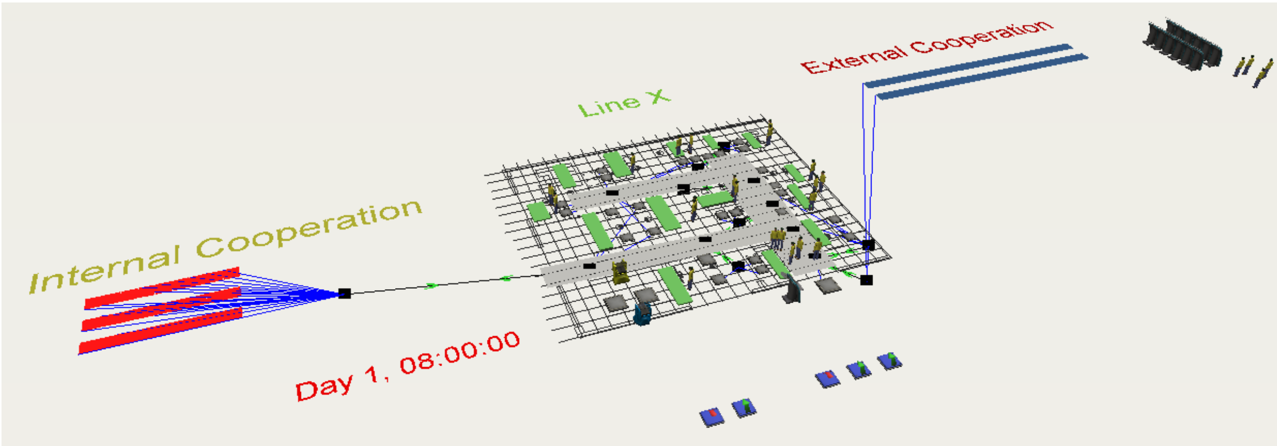


Fig. 1. General view of the simulation model (included cooperation operations) of the whole manufacturing process prepared in FlexSim

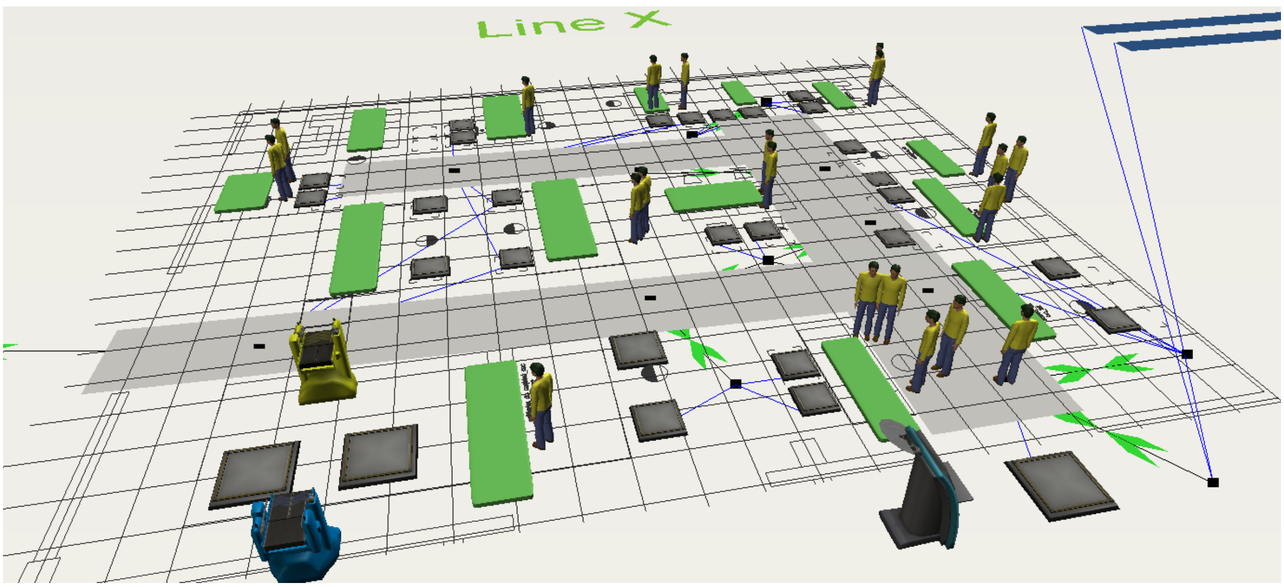
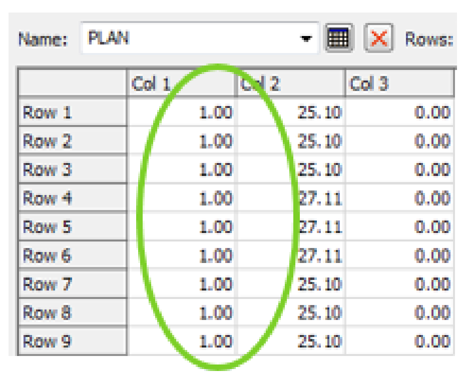


Fig. 2. Detailed view of the simulation model of the analyzed factory department prepared in FlexSim

The production flow was carried out in batches of 10 pieces – the company adopted the batch size as a reference against which the model was validated. The company's engineers validated the model by comparing it against historical and reference data for the modeled line. The company proposed several manufacturing sequence scenarios. The real-life sequence (Sequence 1) was used as a reference for simulation experiments, within which various sequences of introducing products were tested. Tab. 2 shows the results: two sequences with shorter execution times.



Name: PLAN Rows:

	Col 1	Col 2	Col 3
Row 1	1.00	25.10	0.00
Row 2	1.00	25.10	0.00
Row 3	1.00	25.10	0.00
Row 4	1.00	27.11	0.00
Row 5	1.00	27.11	0.00
Row 6	1.00	27.11	0.00
Row 7	1.00	25.10	0.00
Row 8	1.00	25.10	0.00
Row 9	1.00	25.10	0.00

Fig. 3. Plan for 9 production orders with their statuses (column 1) and due dates (column 2)

V. CONCLUSIONS AND DEFINITION OF THE COMPANY'S EXPECTATIONS

The completed project and the results obtained inspired the company to define a new approach to company management, namely, to start preparing production plans with the ability to modify them in a variable environment. A specific decision case was defined, which can be characterized

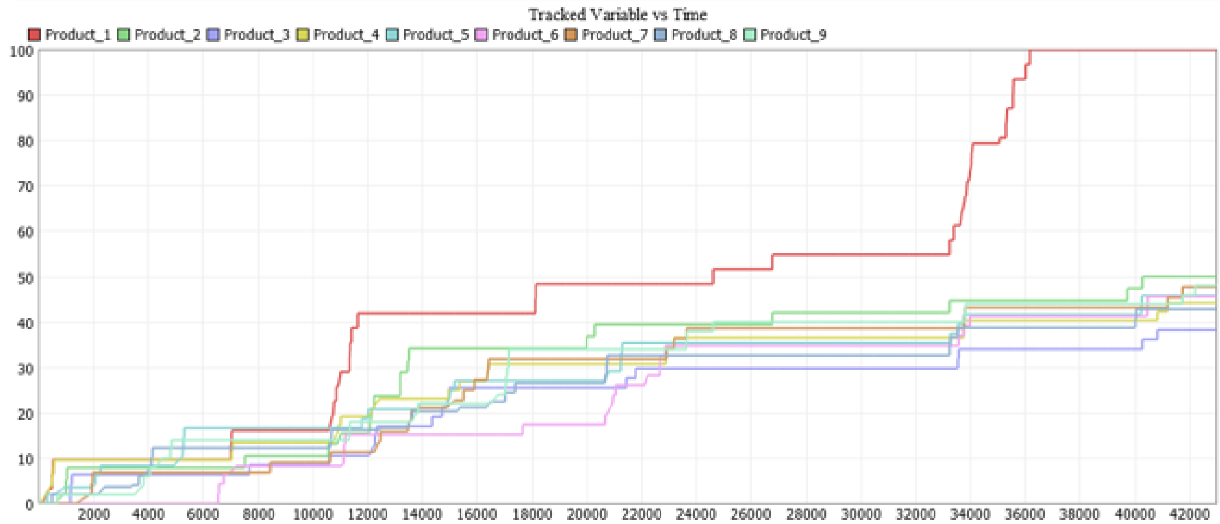


Fig. 4. Graphical representation of the Work-In-Process changes meter in time for the analyzed production sequence of 9 products

by the following question: what decision should be taken in a situation when at a given moment of time several production orders are in progress based on concluded contracts while a new customer appears with another order demanding a short delivery time and ready to pay extra for the quick execution of the new order? Fig. 3 illustrates such a scenario where 9 production orders are listed with their due dates in column 2. Column 1 shows order statuses (1 – in progress, 0 – suspended).

An unexpected (but potentially very profitable) urgent order from a client who wants to pay extra for a quick delivery causes a dilemma for the manufacturer: which (if any?) ongoing orders to suspend for the extra order to squeeze in?

The simulation project delivered a conceptual method for completing such tasks. The method stems from the idea of integrating DES/ABS simulations (DES – Discrete Event Simulation, ABS – Agent Based Simulation) described in the article [13] – where DES constitutes the simulation model sandbox, while ABS allows to describe the action operators structured in routes (cycles). When applying the routes the production plan execution is ensured. The method structures the factory model in such a way that it primarily focuses on locations and operations. Locations are places in the factory that are used to store containers with parts, equipment, and finished goods. Operations are elements of the routes of operators that are required by the product manufacturing process. The step of the method is to observe the location and operations performed.

Location observation lies in checking whether predefined criteria, which are important in the decision-making

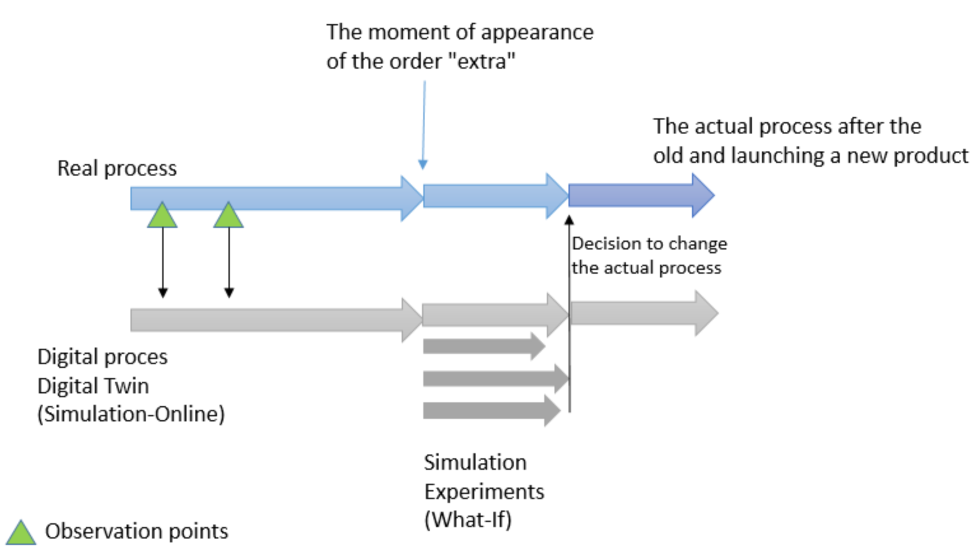


Fig. 5. Integration of the Factory digital twin with simulation experiments

process, have been exceeded/achieved. Examples of the location observation criteria defined for the purposes of the project are as follows:

- is there an empty container at location?
- is there a full container at location?
- has the number of containers in the location reached / exceeded the level defined in the so-called Localization Kanban?
- has the quantity of parts / semi-finished products / finished products reached the level of Container Kanban?

At the same time, the observed stock level (quantity of parts / products) can be later transferred as a state to the simulation model. Observation of an operation lies in checking which operation is being carried out (and the degree of its implementation). For this purpose, the Work-In-Process measure of a given product was developed for the analyzed factory, which is expressed by this formula:

$$[\text{Level of Work in Process}] = \frac{[\text{Sequence No. of Operation}]}{[\text{Total No. of Operations}]} .$$

This measure is determined for each product – Fig. 4 shows the changes of this measure over time for the analyzed sequence of 9 products. The analysis of this measure is necessary to make a decision to suspend a given production order and introduce a new one to production.

The structuring of the factory consists in strict separation between the observation of ongoing operations and the observation points (points on the basis of which decisions are made): so-called locations. The role of the factory digital twin is to observe the locations and operations (data flow from the real model to the digital model) – there is a decision module in the digital twin that decides what action shall be taken when an observation criterion is met (data flow from the digital model to real life). By distinguishing between points of location observations and points of operation observations one can map processes carried out in reality onto the simulation model. As a result, experimental simulations of possible scenarios, starting at specific moments of the real life process, can be carried out – Fig. 5.

VI. CONCLUSIONS

This paper presents an approach to integrating the digital twin with simulation modelling. Reactions of the factory staff participating in the project are promising. The approach requires the factory to isolate observation points from observed operations. This requirement necessitates the introduction of an operator action description language, identical to the one describing employee routes. Consequently, a 1:1 mapping of the factory processes onto the simulation model will be enabled. Such work is already underway and has been described in articles [14, 15](Pawlewski, 2018, Pawlewski 2019). Implementation works of the described solutions are currently underway. The positive feedback of the factory staff was triggered by the following potential benefits:

- Conscious operational management,
- Line rate reduction,
- Increasing the rate of on-time deliveries,
- Increase WipTurn (line turnover indicator),
- Lower aging,
- Flexible solution – impress the customer – seize opportunities in line with Agile Management,
- Competitive advantage – by lowering operating costs.

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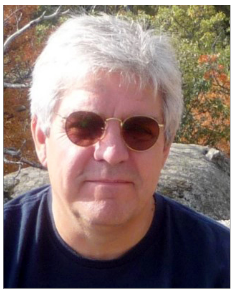

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