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Use of the digital twin concept to optimize the production process of engine blocks manufacturing

Erika Sujová[1*], Roman Bambura[2], Daniela Vysloužilová[3], Peter Koleda[1]

[1] Technical University in Zvolen, Faculty of Technology, Studentska 26, 960 01 Zvolen, Slovak Republic; erika.sujova@tuzvo.sk (ES), peter.koleda@tuzvo.sk (PK)
[2] Asseco CEIT, a.s., Univerzitná 8661/6A, 010 08 Žilina; roman.bambura@asseco-ceit.com
[3] Jan Evangelista Purkyně University in Ústí nad Labem, Faculty of Mechanical Engineering, Pasteurova 3334/7, 400 96 Ústí nad Labem, Czech Republic; daniela.vyslouzilova@ujep.cz
*Correspondence: erika.sujova@tuzvo.sk, Tel.: + 421 907 368 346

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Abstract
The aim of the paper is to present the concept of a digital twin (DT) as part of the Industry 4.0 strategy. In the form of a case study, a digital twin of a production line for the processing of engine blocks is presented, which will serve as a starting point for further research in the field of digitization of production processes. The research part describes the simulation model of the production line with the representation of the material flow as a basis for the creation of a digital twin. The simulation model was used to optimize the production processes of the engine block and to verify the increase in its productivity. A case study implemented through a digital twin enables testing and analysis of changes before they are introduced into real production.

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1. Introduction

In connection with the growing development of information technology, the production industry is moving into the era of so-called "Smart" production. The digital enterprise represents a new phenomenon towards which the concept of Industry 4.0, representing the comprehensive digitization of industry, is heading. The tools of the digital enterprise enable the effective use of information technology when introducing or innovating products and systems. The integration of information and computer technologies with the help of digital enterprise tools creates an environment for displaying real states in the form of computer digital models, which are depicted in a virtual form (Furmann, 2010).

A digital enterprise represents an environment where, with the help of the integration of information and computer technologies and digital enterprise tools, an environment is created for the display of real states in the form of computer digital models that are displayed in a virtual form.

Today, the leaders in the use and implementation of digital enterprise tools are mainly the automotive, engineering and electrotechnical industries. The implementation of digital enterprise tools brings many benefits to large, but also small and medium-sized companies (Furmann, 2017).

The digital enterprise connects people and objects through interconnections in the digital world. Transforming a business into a digital business requires the facts shown in Fig. 9. Enterprise transformation depends primarily on human resources. The people who are available must have the right vision and skills to achieve it (Fusko et al., 2015).

The digital enterprise supports planning, analysis, simulation and optimization of production and products, while creating an environment for teamwork. Digital enterprise tools enable rapid feedback between designers, technologists, production system designers and production planning (Plinta, 2013; Teymourian, 2021; Sira 2022).

According to Kuhn (2006), digital enterprise tools are used for the following activities:

- The product development, testing and optimization.

- The development of the production process and its optimization.
- The design and improvement of enterprise.
- The operational planning and production management.

The goal of our research is to create a digital twin of a real production line focused on processing products for the automotive industry. The digital twin was created with the help of simulation digital models in Siemens' Tecnomatix Plant Simulation software. The simulation model was subsequently verified and validated according to the real production line it copies. Using PLC controllers, it was possible to collect data in real time into the SQL database, which was subsequently connected to the simulation digital model.

2. Literature review

A digital twin (DT) is a digital representation of a physical object, process or service. A digital twin replicates processes in order to collect data from the real world on the basis of which it simulates and predicts the behaviour of a physical object in the virtual world.

The concept of DT as we know it today was first described by Grieves (2014) in 2003. He divided it into three dimensions, hence the name three-dimensional DT. The individual parts of DT were divided into the physical world, the virtual world, and the connections between them.

The next significant turning point in the development of DT was the year 2010, when Shafto et al. (2010) from NASA described and defined the function of this concept in the publication "Draft Modeling, Simulation, Information Technology and Processing Roadmap". The definition was followed up by Tuegel et al. (2011) and the United States Air Force (U.S. Air Force) with the aim to explore DT applications for aircraft condition monitoring and management. In 2012, NASA and the U.S. The Air Force jointly published a study on the use of DT that describes the concept as key to future research and development of space vehicles and aircraft (Tuegel, 2012). In 2014, there was widespread promotion of the three-dimensional DT structure, which resulted in the introduction of this concept to several areas outside the aerospace industry (Grieves, 2014). Damiani et al. (2018) noted a significant increase in the number of publications on the topic of DT in 2017.

The concept of DT is considered one of the most advanced technological trends for the next decade, which aims to connect virtually all digital aspects with their copies in the real world, with the vision that billions of things will be constitute DT in the near future (Ahmed, 2017; Panetta K., 2017; Panetta K., 2018).

An interesting interpretation of DT is provided by Kritzinger et al. (2018), which gives a literature review on DT depending on interactions between a physical object and a relative virtual object. In this sense, a proper DT is one in which virtual objects exchange data with physical objects in both directions. This means that the virtual object can eventually act on the control system of the real object.

According to Cimino et al. (2019) the challenge is when providing these services in one environment results in some of them needing a 3D graphical interface and others analysing data without the need for any graphics. It is also clear that some of them (e.g. "Intelligent optimization and updating") are based on this mutual exchange of information between the real and the virtual object.

The main advantages of DT include:

- It reflects the structure, performance, health status and characteristic features of the physical twin.
- The evaluation of the current and future capability of the system during the entire life cycle.
- It plans preventive maintenance based on knowledge of maintenance history and observed behaviour of the system.
- It helps to understand how a physical twin works in the real world.
- The predictive analysis based on collected data.
- It predicts the future productivity of the system.
- The optimization of service and production processes.
- The identification of design improvement.
- The continuous refinement and improvement through captured data (Leiva, Strategy, 2016; Madni et al., 2019).

DT integrates technologies to achieve monitoring, simulation, diagnosis and prognosis. Monitoring requires computer graphics, image processing, 3D rendering and synchronization. Tools such as MindSphere, Thingworx, 3D Experience, etc. are used for this purpose. Simulation includes simulation of construction, control, process, and virtual testing using simulation tools such as PlantSimulation, Ansys, Witness, Simulink, etc. Diagnosis and prognosis are based on data analysis, using statistical methods (Qi et al., 2019; Fuller et al., 2020).

The main role of DT in the production phase is to optimize production processes, increase flexibility, productivity and quality of production and reduce production costs and energy consumption. Here are some examples of DT implementation for optimization and improvement of production processes:

- The company Embraco created a DT of the production line, which goal was to monitor the operation in real time and, based on the operational data from the previous day, to evaluate the behaviour of the production line. Such a DT application made it possible to increase Overall Equipment Effectiveness (OEE) by + 3%, to visualize the current but also the historical state of the production line, to determine cycle times, to record downtimes and micro-downtimes to improve planning (Mitana 2018; Gérer 2018).
- The company Secop created a DT on the assembly line to produce compressors, which enabled identification of blocking, online monitoring of production and evaluation of Key Performance Indicators (KPI) (Ondrejmiška et al., 2019; Industry4um.sk. sidat.cz).
- Židek et al. (2020) proposed DT as a quality control and identification system to maximize the use of collected data from the product quality control process.
- DT for parallel control of intelligent workshop by Leng et al. (2019) helped with equipment configuration and operation. System productivity analysis prevented costly and long-term decisions in dynamic process optimization.

- DT of the manufacturing company for product packaging at Prolim enterprise enabled the simulation of the number of workers and changes to identify the return and utilization of resources and KPI analysis (prolim.com 2020).
- Zhuang et al. (2018) used DT on an assembly line, whereby using DT he was able to reduce the negative impact of uncertainties, reduce assembly costs, increase product quality and productivity.

The digitization of production processes and the concept of a digital twin are being dealt with by leading global organizations. National and international programs and projects are being created to support digitization. However, this trend is also the subject of research. Individual universities are increasingly investing in the construction of laboratories designed to investigate the effects and use of digitization, the digital twin and other Industry 4.0 technologies for production as well as non-production processes. The issue of the digital enterprise and the use of its tools in the optimization of production and non-production processes are dealt with by many important world authors (Plinta, 2013; Palčič et al., 2020; Kühn, 2006; Hajba et al., 2017; Biesinger et al., 2018; Bučková et al., 2017).

3. Materials and Methods

The goal of the research is to create simulation digital models of production lines and then connect them with real production lines and create a digital twin (DT). A case study was conducted in a manufacturing company, the aim of which was to create a DT production line for machining aluminium alloy engine blocks, which is fully automated (Bambura, 2021). The required result of the case study and the conducted experiment is that the digital twin can simulate the production process in real time in a virtual space.

The production process to produce aluminium alloy engine blocks includes melting, storage, cleaning and removal of excess castings, heat treatment and machining. The subject of this study is only the machining part of the production process. After the engine block casting process, it is necessary to carry out several different machining processes that are carried out on engine block machining production lines. Fig. 1 shows a visualization of the analysed production line.

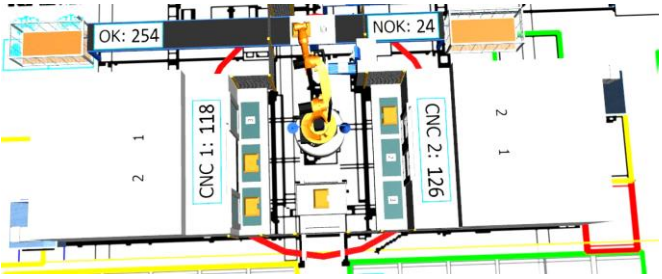

Fig. 1. Visualization of the production line for the machining of engine blocks including the indicated current number of machined castings (Bambura, 2021)

The production line is fully automated and consists of the following parts:

- CNC machining centres – CNC 1 and CNC 2,
- robotic arm,
- input conveyor,
- output conveyor for matching castings (OK) and for non-matching castings (NOK),
- measuring device,
- inspection entrance,
- magazines for CNC,
- magazines for mismatched castings.

Below is a brief description of the activity of the analysed production line. The robotic arm operates all the listed production equipment. After loading the CNC 1 device, the robot will start to operate CNC 2 while CNC 1 is machining. For the optimal operation of the production process, it is essential that the input conveyor delivers castings for processing and at the same time that the operators at the end of the output conveyor remove already processed castings. The absence of a casting at the entrance affects the duration of the cycle time and, consequently, the total production during one working hour. In the case of a full output conveyor, the production station cannot continue its operation until there is free space on the conveyor, which also increases the cycle time and reduces the overall production. The production process for processing castings on the production line is shown in Fig. 2.

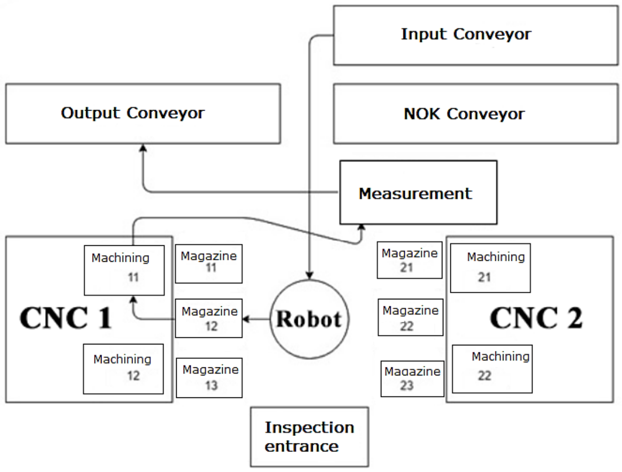

Fig. 2. Schematic representation of the processing of one casting on the production line

The optimization of the described production system was carried out through a simulation experiment (Fig. 3) (Bambura, 2020).

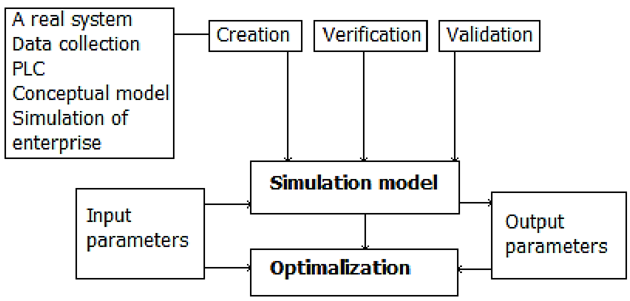

Fig. 3 Design of the simulation experiment procedure

The goal of a computer simulation is to duplicate a real production system. By using it as an experimental method, it is possible to conduct experiments and analyse their results, evaluate, and subsequently optimize production processes in the virtual world, without affecting the real subject of research. Individual changes can subsequently be implemented in a real production line. The first step was the evaluation of the current state of the production line and the description of the tools necessary for the creation of the DT and the subsequent execution of the experiment.

4. Research results

The main goal of the case study was to create a digital twin of the production line on which engine blocks are processed. As part of the solution, a simulation of the production line was developed with the subsequent collection and implementation of data into the simulation to evaluate the behaviour of the production line. The simulation was created, verified, and validated according to the real production line (Fig. 4) in the Tecnomatix Plant Simulation software. The digital twin consists of three layers: physical, virtual and information processing. The digital twin acquires data and information about the status of the production line from the physical layer using PLC controllers and the information processing layer. It simulates production processes using programmed methods in the Sim talk 2.0 programming language. It also visually copies a real production line. The digital twin allows remote monitoring of the production process, a look at the KPI of the production line in the form of charts and the detection of errors and bottlenecks on the production line.

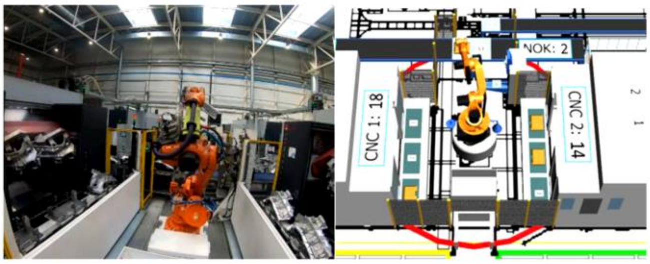

Fig. 4 View of a real production line with a robotic arm and its simulation model (Bambura, 2021)

For our case study, the throughput of the production line, which represents the interval of occurrence of castings at a given point and at a given time, was chosen as the observed parameter. The throughput chart of the production line (Fig. 5) is created with the help of a table (Table 1 in Appendix A).

Table 1 contains information about the descriptive number of the casting, the time data on its exit from the system and the assigned conveyor through which the workpiece passed, in order to distinguish matching - OK and non-conforming - NOK workpieces. It also includes information about which CNC the workpiece was machined on, or whether it is a workpiece that entered the system through the inspection input after manual finishing for additional dimensional control at the measuring station.

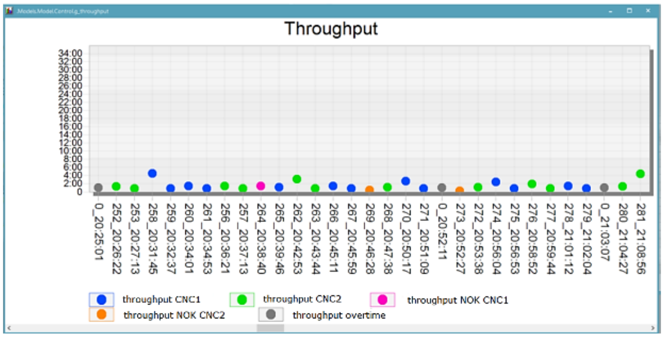

Fig. 5 Graphic representation of production line throughput (Bambura, 2021)

Based on the obtained data, it is possible to better comprehend the ongoing processes on the production line and subsequently optimize it to increase its production.

Based on the analysis of the data from the digital twin, it was possible to reveal bottlenecks in the production line. DT provides a new perspective on production line behaviour and management. The results from DT show that the output OK conveyor and the measuring station have the greatest influence on the throughput of the production line. In addition, the output conveyor is affected by the human factor. A worker must remove a casting from the process at the end of the conveyor to make space for the robot to place the next casting after machining, measuring, and cutting out.

To simulate the behaviour of the production line after the removal of the bottleneck, the "m_ideal_conveyor" method was created in SimTalk 2.0. The method ensured the automatic removal of the casting from the output OK and NOK conveyor immediately after it was placed by the robot.

Minimization the occurrence of a bottleneck on the output conveyors consisted in the installation of a light signalling device (Schneider Electric XVBC2B6) on the output OK conveyor. In case that the output OK conveyor is filled and thus blocks the operation of the robot, the light signalling device will warn the workers to remove the workpieces from the conveyor. A sound signalization (Schneider Electric XVBC9B) was placed on the output NOK conveyor. Workers who operate the input conveyor also remove workpieces from the NOK conveyor. After applying the changes to the production system, the digital twin was restarted and the impact of the optimization on the throughput and overall productivity of the production line was analysed.

Based on the statistical results (Table 2 in Appendix B) from the digital twin for the optimized production line, it can be observed a significant improvement in throughput on the production line. The individual deviations that occurred in the original production line were significantly reduced, which contributes to the elimination of equipment blocking on the production line and thus to an increase in production and throughput of the production line.

5. Discussion

Our research was focused on the creation of a digital twin of the production line, used for the processing of engine blocks, using the tools of a digital enterprise and its optimization based on the data obtained from the digital twin. The digital twin of the production line consists of three layers: physical, virtual and an information processing layer, which together make it possible to describe and copy a real production line in a digital environment. The virtual layer is used to create simulation digital models in the Tecnomatix Plant Simulation software. Where individual objects are programmed to behave like a real production line using the SimTalk 2.0 programming language. The information processing layer serves to collect, transmit and archive data collected by sensors and represents a "bridge" that connects the physical and virtual layers.

With the help of the case study, it was possible to create a digital twin and subsequently analyse and optimize the production line for the processing of engine blocks. It also serves as a starting point for further research in the field of digitization of production processes. The presented digital twin can be developed in the future through more detailed processing and data collection (energy consumption, data on CNC processes, etc.). Subsequently, it is possible to carry out research, for example, in the field of planning preventive maintenance of equipment based on knowledge of maintenance history and observed behaviour of the system.

The key productivity indicator of the analysed production line was determined to be the throughput parameter, which expresses the interval of occurrence of castings at a given point and at a given time. Based on the analysis of data from DT, it was found that output conveyors, which block the operation of the robot during filling, have the greatest impact on the throughput of the production line. By minimizing the occurrence of the identified bottleneck on the output conveyors, an increase in production was achieved, as shown in Fig. 6.

To verify the effectiveness of the optimization measures, a bar graph (Fig. 6) was created that compares production on the production line during one work week, which represents 15 work shifts. Compared to this, a significant increase in production can be observed.

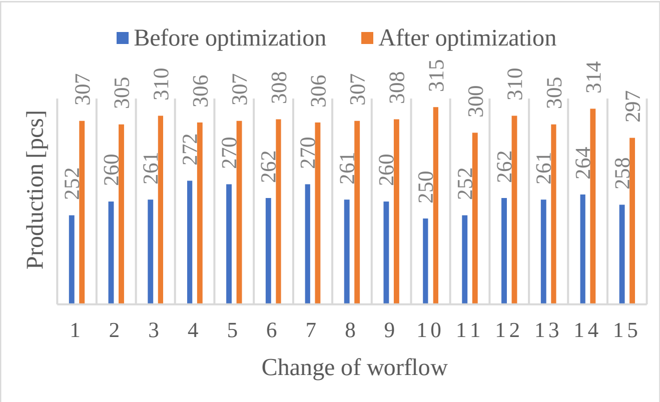

Fig. 6 Comparison of production on a production line during one working week (15 shifts)

6. Summary and conclusion

The creation of a digital twin of production systems with the support of Industry 4.0 technologies provides manufacturing companies with an opportunity to flexibly react to market changes. It helps them to better understand production processes and subsequently optimize them using the large amount of data that can be obtained from DT.

The aim of the presented case study was the creation of a digital twin of a production line for processing aluminium engine blocks, using the tools of a digital enterprise and its optimization based on the data obtained from the digital twin. A digital twin consists of three layers: physical, virtual, and a layer for information processing. The physical layer represents the individual devices and sensors on the physical production line. Subsequently, a simulation model of the production line was created in the virtual layer, which represents the real production line. In the first phase, it was necessary for the simulation model to behave like a real production line. The logical sequence of operations and the behaviour of the virtual production line were programmed using the TPS software using the Sim Talk 2.0 programming language. The simulation model was verified and validated according to the actual production line. Individual production data were implemented into the simulation model and, based on the measurement of individual cycle times, the output data from the virtual and real production line were compared, which made it possible to verify and acquire the agreement of the virtual and real production line and its logic. To create a DT, it is necessary for the virtual and physical layers to communicate with each other. The information processing layer serves to connect the virtual and physical layers. Individual key data collection points were determined in the production line, whose signals and addresses were recorded using PLC controllers and implemented in the virtual layer. The throughput of the production line was chosen as the key parameter for the case study, which expresses the interval of occurrence of castings at a given point and at a given time. A comparison of production line production for the monitored period of one working week showed an 11-20% increase in productivity in the optimized model.

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Appendix A

Table 1. Statistics on **production** line throughput (Bambura, 2021)

Partnumber	Out	Throughput CNC1	Throughput CNC2	Throughput NOK CNC1	Throughput NOK CNC2	Throughput overtime
37_14:24:54	2020/12/09 14:24:54					
31_14:27:29	2020/12/09 14:27:29	2:35.0000				
32_14:28:21	2020/12/09 14:28:21	52.0000				
33_14:30:02	2020/12/09 14:30:02		1:41.0000			
34_14:31:56	2020/12/09 14:31:56				1:54.0000	
35_14:33:19	2020/12/09 14:33:19	1:23.0000				
36_14:34:11	2020/12/09 14:34:11	52.0000				
45_14:34:20	2020/12/09 14:34:20					
38_14:36:20	2020/12/09 14:36:20		2:00.0000			
39_14:37:10	2020/12/09 14:37:10		50.0000			
40_14:38:34	2020/12/09 14:38:34	1:24.0000				
41_14:39:26	2020/12/09 14:39:26	52.0000				
42_14:41:41	2020/12/09 14:41:41		2:15.0000			
43_14:42:32	2020/12/09 14:42:32		51.0000			
44_14:43:57	2020/12/09 14:43:57	1:25.0000				
46_14:44:46	2020/12/09 14:44:46	49.0000				
0_14:45:49	2020/12/09 14:45:49					1:03.0000
47_14:47:07	2020/12/09 14:47:07		1:18.0000			
48_14:47:54	2020/12/09 14:47:54		47.0000			
0_14:49:04	2020/12/09 14:49:04					1:10.0000
0_14:50:22	2020/12/09 14:50:22					1:18.0000
0_14:52:03	2020/12/09 14:52:03					1:41.0000
0_14:56:33	2020/12/09 14:56:33					4:30.0000
0_14:58:48	2020/12/09 14:58:48					2:15.0000
49_15:00:37	2020/12/09 15:00:37	1:49.0000				
50_15:01:29	2020/12/09 15:01:29	52.0000				
...	...	...	...	...	...	...

Appendix B

Table 2. Deviations arising on the production line after its optimalization

Operation	MIN	MAX	AVG	MODUS	NUM	SUM	ST_DEV	Frequency
212A-111B	3	175	37.8	3	5	189	76.7	1
513A-511A	0	8	1.33	0	6	8	3.27	1
512A-121B	6	60	11.0	6	13	143	14.98	2
122A-511A	1	39	7.5	1	6	45	15.44	2
513A-523B	11	333	37.3	12	20	746	81.92	2
512A-514B	8	400	43.07	8	14	603	103.89	4
301A-301B	7	353	10.27	8	321	3297	21.92	7
301B-512A	4	1423	10.63	5	308	3274	81.17	9
512A-522B	1	114	7.37	6	307	2263	10.27	15
212A-121B	6	94	15.35	7	49	752	14.91	20
222A-111B	6	147	21.06	7	51	1074	23.42	27
524A-514B	5	412	84.79	5	48	4070	74.7	43
521A-511B	5	1434	53.32	19	279	14877	97.21	126

使用数字孪生概念来优化发动机组制造的生产过程

關鍵詞
工业4.0战略
仿真模型
生产线
生产流程的优化

摘要
本文旨在介绍作为工业4.0战略一部分的数字双胞胎（DT）的概念。以案例研究的形式，介绍了一条加工发动机组的生产线的数字双胞胎，这将作为生产过程数字化领域进一步研究的出发点。研究部分描述了生产线的仿真模型，其中包括作为创建数字双胞胎的基础的材料流。仿真模型被用来优化发动机组的生产过程并验证其生产力的提高。通过数字孪生体实施的案例研究能够在将变化引入实际生产之前对其进行测试和分析。