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SIMULATION BASED HIGH FIDELITY DIGITAL TWINS OF MANUFACTURING SYSTEMS: AN APPLICATION MODEL AND INDUSTRIAL USE CASE

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ABSTRACT

Modern manufacturing systems are required to be developed, commissioned, and reconfigured faster than ever before. Conventional methods for the development of manufacturing systems are time-consuming due to their sequential nature. A digital twin is an emerging technology that can offer a high-fidelity simulation of a real manufacturing system including its kinematics, automation program, behavior, user interface, and production parameters. Such a unified digital twin can be used as a support tool for verification and validation of complex behavior of modern-day manufacturing systems during design, commissioning, reconfiguration, maintenance, and for end-of-life. The resulting benefits are to speed up the development and reconfiguration phases and improve system reliability. This article presents a framework to develop and use a digital twin for the development of complex machines. An industrial case from a large automation company is presented.

1 INTRODUCTION

A system can be defined as an organized group of resources that work together as a mechanism (Wiendahl et al., 2015). Factories are often referred to as manufacturing systems because they comprise of a range of resources that work together to produce a common product. Setting up a new factory or its sub systems is a challenging and complex task. Similarly, the reconfigurability is becoming challenging and time consuming. Additionally, the concepts of Industry 4.0 have given rise to complexity in manufacturing systems (Malik & Brem, 2021). Complexity refers to the information content and predictability of a system. While modern manufacturing systems are increasingly being desired to be adaptable, reconfigurable, and resilient to adapt to market fluctuations (Wang et al., 2019), they are also desired to be developed fast and accurate (Jeon & Schuesslbauer, 2020).

The traditional development of a new manufacturing system takes considerable time. To verify and validate a design of a manufacturing system, 3-dimensional close-to-reality virtual models make it possible to investigate the dynamic behavior of a system being developed (Mourtzis et al., 2015). However, virtual models remain standalone virtual artefacts and remain limited to simulation of kinematic behavior of the devices. Automation program and production behavior are investigated later during the commissioning phase (Ganesan & Dharmaraj, 2020). This can cause several errors in the automation program that may require error identification, corrections, and rework.

Furthermore, the traditional development of machine tools and manufacturing systems takes the verification of the control program as the last step. This approach may extend the development time; additionally any errors encountered at this stage can cause delay in time to market resulting in economic loss (Ugarte Querejeta et al., 2022). The approach of virtual commissioning (VC) suggests to utilize computer-based simulation models to test errors early in the design phase (Kuhn et al., 2022).

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Digital twin is a technology that refers to a virtual representation of the dynamics, and elements of a physical system (Cheng et al., 2018). Digital twin technology has been explored in different application domains such as manufacturing, robotics, spaceships, wind turbines etc. (Leng et al., 2021). The concept of digital twins in manufacturing applications is an evolution of computer simulations but adds a lifecycle approach, data connectivity (Shao et al., 2019) and a degree of intelligence. A DT (developed during the design phase) accompanies its physical system throughout the various phases of life cycle such as for the development and for the operational phase (e.g. maintenance and reconfigurations and also for the end of life.

This article explores the usability of digital twin in development of manufacturing systems. The goal is to reduce the development time of complex mechatronic machines by creating unified and accurate virtual models of manufacturing systems that support the verification and validation in less time than conventional system development methods. Thereby the development phases become more parallel or concurrent. This article presents:

1. A framework based on a unified digital twin to support verification, validation and control along system development lifecycle
2. Defining the business value of applying digital twin in system development
3. An industrial use case to validate the proposed framework

2 RELATED WORK

Virtual manufacturing (VM) is the use of virtual models for design verification, development, and commissioning of manufacturing systems (Souza et al., 2006). VM is based on computer models that represent the whole structure of a manufacturing system and simulate its kinematic and logical behavior. Due to shortened manufacturing cycles and fierce market competition, the development and commissioning time of manufacturing systems has been reduced by using the technologies of virtual commissioning, HiL (hardware in the loop) and SiL (software in the loop) in automotive manufacturing especially when involving robotics (Makris et al., 2012) (Gustafsson & Gustavsson, 2019) (Ganesan & Dharmaraj, 2020).

In this regard, the design and commissioning of a variant oriented smart phones assembly line by using a digital twin was presented by (Yan et al., 2022). The digital twin was utilized to develop parallel control from the physical world to the digital world and accelerate the design process. A methodology for virtual commissioning digital twin was presented by (Barbieri et al., 2021). The suggested method is a step wise formation of designing, integrating, and verifying a simulation. Another digital twin driven assembly commissioning for high precision products was presented by (Sun et al., 2020). The usefulness of digital twins for accelerated reconfiguration and validation of manufacturing systems involving robotics has been argued by (Malik et al., 2020).

A challenge in virtual commissioning is the unavailability of a unified simulation environment that incorporates different variables of a manufacturing system. To address the challenge, a four layer architecture model for development of a digital twin was presented by (Ugarte Querejeta et al., 2022). The model consisted of a physical layer (hardware controllers), cyber layer (simulation of the physical layer), middleware (that incorporates data exchange through open standard protocols) and application layer (to save retrieved data for analysis). The model was tested in the development of assembly line of solar panels and gained time reduction benefits in mechanical design, electrical design, and control logic.

3 DTXD: DIGITAL TWIN BASED MANUFACTURING SYSTEM DEVELOPMENT

This section presents a framework to create a high-fidelity digital twin of a manufacturing system that can be used along its lifecycle to reduce the development time and improve operational efficiency. A digital twin of a manufacturing system is a unified simulated environment based on different computer simulations (see Figure 1). Each simulation is modeled to simulate different properties. When all the different simulations are run in parallel with bidirectional data exchange between each other a holistic simulation or a digital twin of the manufacturing system (under observation) is created.

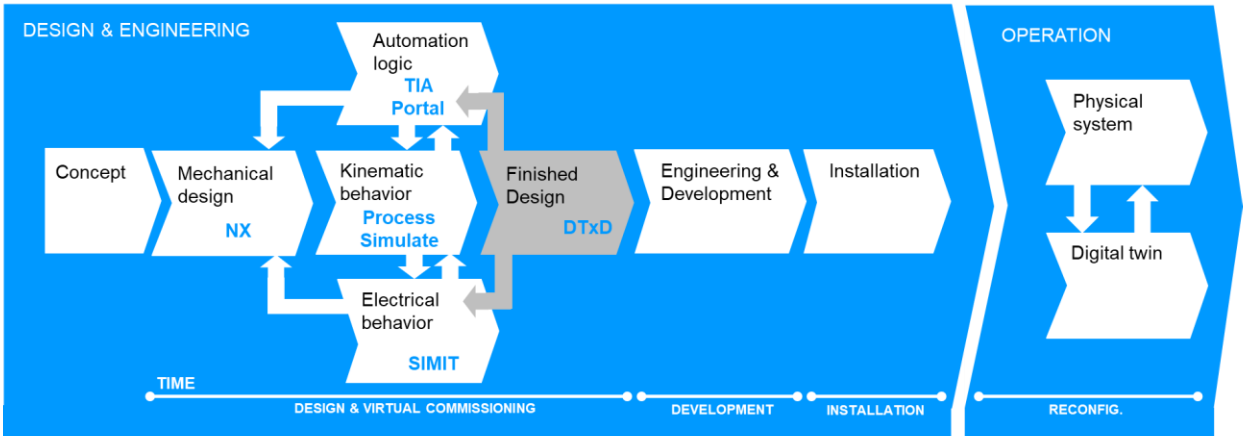

Figure 1: Framework to create and use a digital twin in system development.

The system development framework has two key dimensions that are explained below:

3.1 Building blocks of a digital twin asset

3.1.1 Virtual devices

To build a virtual manufacturing system, the first step is to build virtual devices. Virtual devices are the accurate kinematic simulation of devices in a manufacturing system. Quite often it is a continuous simulation based on agent-based modeling. It requires that each component of the machine is accurately defined including its geometric, physical properties, joints types, joint limits, velocity limits etc. The result of this step is a kinetically defined simulation of a mechanical system. Several analyses (such as collisions, layout assessment, cycle time estimates etc.) and optimizations can already be made at this stage. There are several off the shelf proprietary tools that can be used for this purpose. Additionally, open source engines such as Unity, Unreal Engine can also be used.

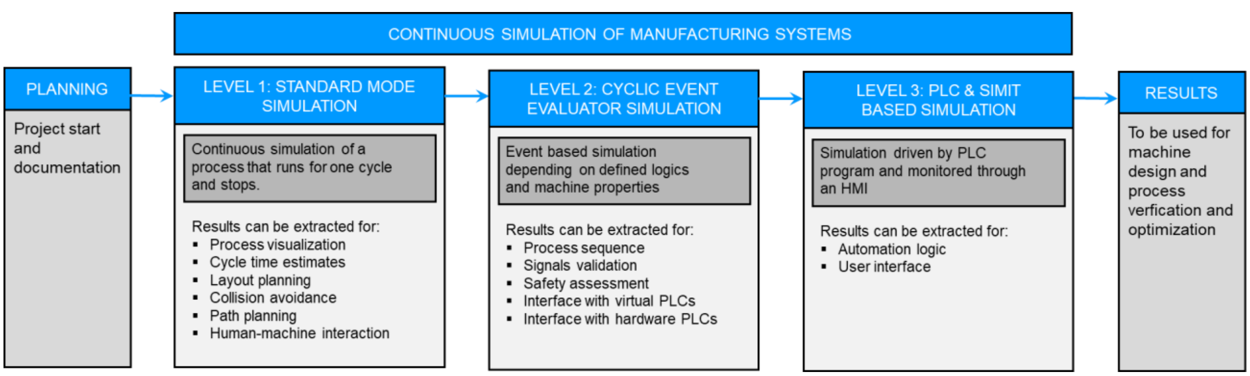

Figure 2: Creating virtual devices for digital twin of a manufacturing system.

The kinematic simulation of a manufacturing system can be divided into three steps (Figure 2). The first step is to create a basic model and its operations sequence. The operations sequence is managed as in a Gantt chart. The next step is to convert it into a cyclic simulation which is a continuous simulation that keeps running until it is stopped. A basic logic behavior is defined and the simulation keeps running as long as the logics are fulfilled. The third step is a high-fidelity digital twin that communicates with areal or virtual PLC (Programable Logic Controller).

3.1.2 Emulated industrial computers

PLCs are industrial computers used to program and control industrial devices (see Figure 3). It is a fundamental step in commissioning of a manufacturing system to create and validate an automation program. Conventionally, this step is carried out once the manufacturing system has been developed and is ready to commission. However, the proposed framework suggests to create the automation program already during the design phase. The validated program at this stage will also serve as an automation code for the real PLCs.

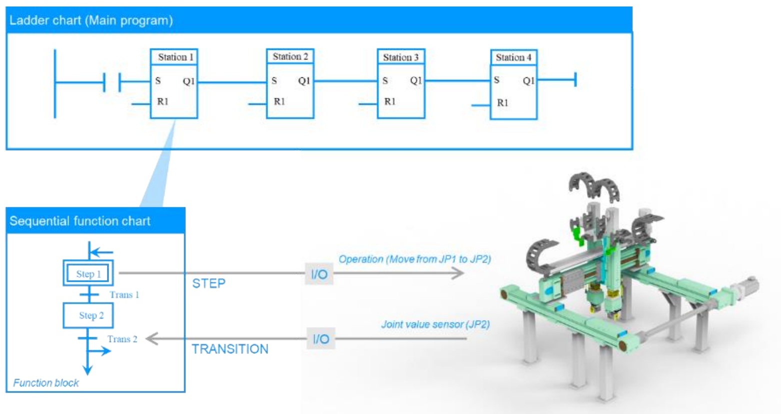

Figure 3: Automation program to control a cartesian robot.

3.1.3 Human-machine interface

Human-machine interfaces (HMIs) are used in industrial settings to enable operators to interact with manufacturing systems, machines or robots to pass instructions e.g. start/stop/speed-adjustment/trouble shooting etc. An HMI is needed in the proposed framework to enable the end user to interact with the simulation model in a simplified way. Touch screen HMIs are common in industrial settings for the said purpose. An emulated HMI is a virtual interface in computer that can communicate with other emulators (such as PLC and virtual machines). Other forms of HMIs can be augmented reality, mobile devices, and wearable computers. The HMI created at this stage will also be downloaded to real HMI for field application.

3.1.4 Virtual controller

The automation program created in the virtual PLC is then loaded into a virtual controller. The virtual controller emulates the functions of the automation program and transmit them to the kinematic simulation of the manufacturing system without requiring any physical devices or connection. The virtual controller is comprising of its own virtual processing unit and virtual ethernet communication protocols. PLCSim Advanced is an open interface that can be used to connect different simulation environments. OPC UA and MQTT are other examples that can bridge the connection between virtual PLC and virtual assets. The end result is a combined simulation of mechanics and automation logic.

3.2 Digital twin along lifecycle phases of a manufacturing system

3.2.1 DT-Design

The design of a manufacturing system involves its conformance to predefined requirements. A system is often an assembly of several components, devices, sensors, actuators, and robots. When developing a new physical system, a digital twin is often developed earlier than the physical twin. It can help to generate and validate the initial design, behavior, layout etc. Although, at the design phase, the corresponding physical twin is not existing, the DT-Design is still referring to a hypothetical future physical twin. Even without a real-time connectivity, the digital twin of the production system can make it possible to experiment several what-if scenarios for achieving faster, safer and better design.

3.2.2 DT-Commissioning

At the commissioning stage it becomes possible to make first trials of the developed system. It is possible to interface the hardware with virtual machine through TCP/IP protocol or through PLCs. The actions initiated at hardware should emulate the resulting behavior in the virtual environment (Figure 4). An example is that a robot connected with a virtual robot can be maneuvered to perform a certain task. However, the physical space is empty but the virtual space is populated with all the hardware and humans. Any likelihood of a collision or problem will be tested in the virtual environment.

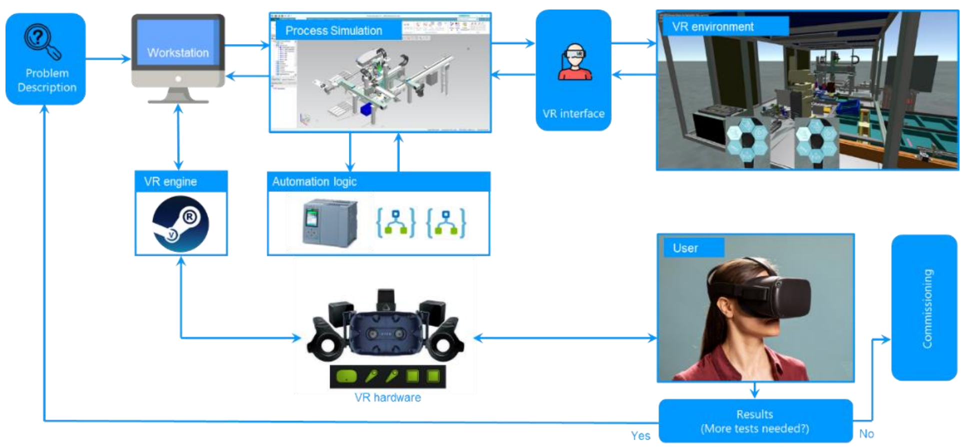

Figure 4: Virtual reality (VR) combined with PLC based simulation of a manufacturing system.

3.2.3 DT-Operations and reconfigurations

Digital twins have the potential to play a pivotal role in helping manufacturing systems respond effectively to market fluctuations. Additionally, the training of operators and monitoring can benefit from digital twins. Reconfiguring may be required in case of product variants, change in product design or due to variation in demand and supply. A virtual environment or a digital twin will help to do the optimization, create new automation program, validate it, and implement it. Maintenance is also an integral part of most (if not all) production systems. Mixed reality technologies such as augmented reality (AR) or chatbots can be integrated with a DT to enable maintenance personnel for better maintenance, fault detection and training.

4 INDUSTRIAL USE CASE

The use case is from a manufacturer of industrial automation equipment. The company is headquartered in Germany that represents a high wage economy. The automation equipment manufactured by the company consists of electric drives, pneumatic actuators, industrial automation sensors and robotic devices. These devices are used in various machine tools by machine builders. When developing a new machine, it takes considerable time to validate a new design, changes occur throughout the development phase due to unidentified errors, and the delay in the development results in direct financial loss (e.g. salaries), and indirect (e.g. opportunity cost).

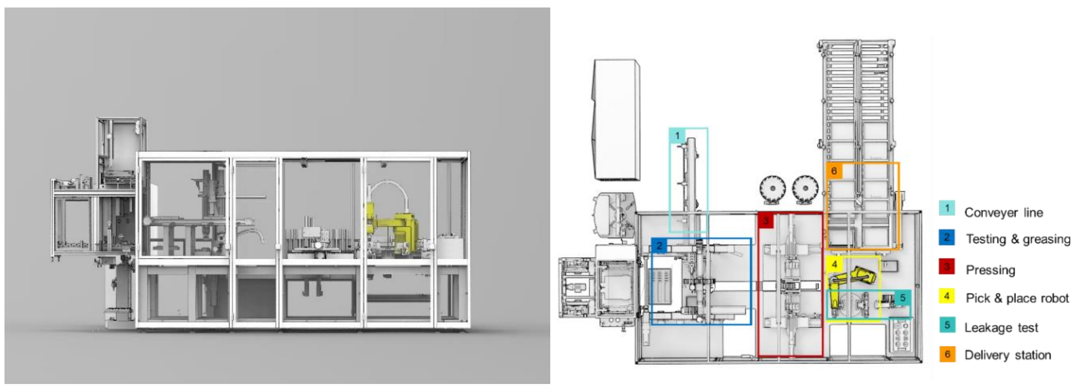

Figure 5: Use case manufacturing system and its sections.

The use case is a manufacturing system used for production of valve assembly (see Figure 5). The manufacturing system can be divided into six sections i.e. cartesian robot, ring pressing, leakage test and delivery robot. There are various sensors, actuators, drives and electronic actuators used in each of the sections. Each cycle of the system lasts 90 seconds and the machine produces almost 280 components per day in a single shift. It is a complex scenario where several tasks must run in parallel. Additionally, the behavior of all the devices needs to be accurately modelled to develop a high-fidelity digital twin (see Figure 6).

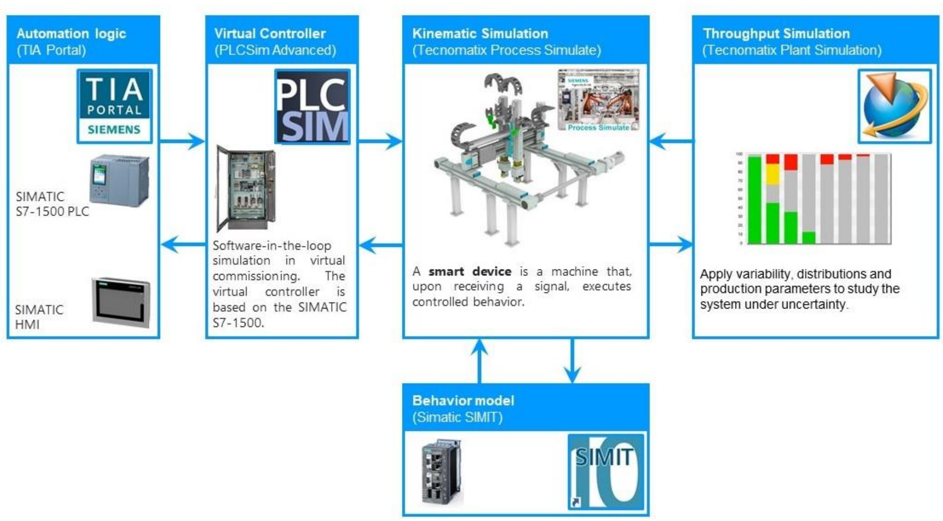

Figure 6: Architecture of the simulation based digital twin of a mechatronic manufacturing system.

The structural and mechanical design is a detailed process driven by the customer expectations. Once a detailed design is achieved and is locked, bill of material and bill of processes are generated. Further details of the mechanical design and components specifications is out of scope of this article.

The CAD models are then exported into a kinematic simulation software in JT format. The tool used in this example is Tecnomatix Process Simulate which is a continuous simulation software. Each device is defined for its performance, kinematic joint constraints, and correlation with the rest of the system (Figure 7). The complete simulation of the system is then run to identify if it works as desired. To make the simulation communicate with other virtual devices I/O signals for each device and its corresponding action were defined. The set of signals are then exported to function blocks where the corresponding behavior of each signal for a given device is defined. Each signal is also interfaced with an External virtual controller.

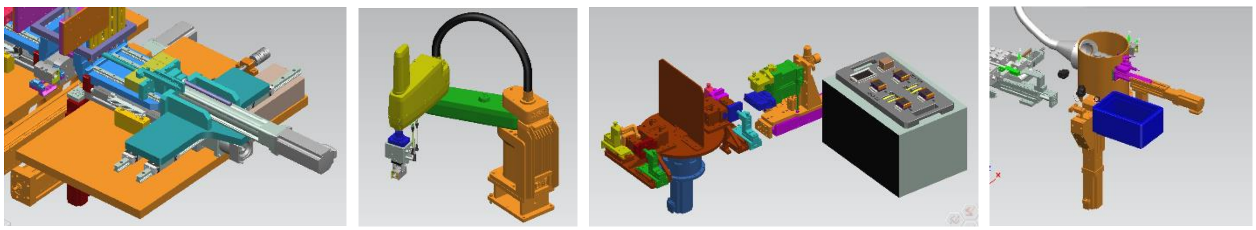

Figure 7: Kinematically defined hardware resources.

The automation is programmed in programmable logic controllers (PLCs) that drive an equipment based on a logical behavior. The PLC used in this example is S7 1500 by Siemens. Instead of using a physical PLC, a virtual PLC is used to emulate its behavior. Total Integrated Automation (TIA) can be used to program and emulate Siemens based PLCs. The automation program for the subject machine is coded in TIA Portal. An advantage of this approach is that the validated program can later be downloaded to the real PLC to control the real machine, hence the automation program development time is reduced.

The automation program in TIA is written in two parts. There is a main Function Block that consists of several Logic Blocks. A separate Logic Block is defined for each section of the machine (i.e. gantry robot, pressing station, robot and quality test). It improves the readability and editing of the code. Each Logic Block consists of a series of Logic Functions (processes) in a sequential architecture.

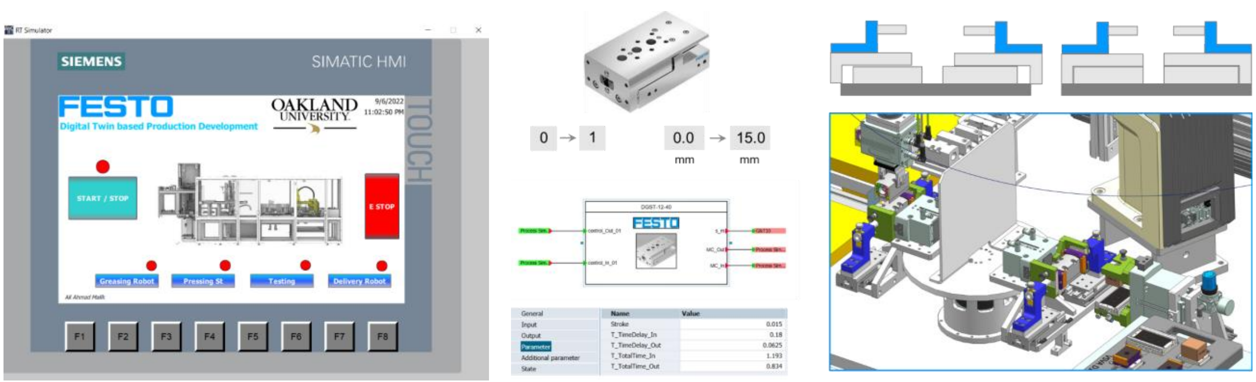

Figure 8: Behavior modeling and human-machine interface.

Electronic behavior of the of devices, sensors, and actuators was modeled in SIMIT software (Figure 8). A FB is modeled for each device. The digital twin helped to identify errors, optimize the design, and validate a final design in less time. The users reported an estimated 20 to 25 percent reduction in the work hours associated with development and commissioning.

5 ECONOMIC IMPACT OF DIGITAL-TWIN BASED SYSTEMS DEVELOPMENT

Besides speeding up the commissioning efforts, VC can avoid several delays due to unforeseen or unpredicted errors that appear during commissioning. Between 70 to 90% time during commissioning can be taken up by delays of which errors in control program can be a major source of delays (Reinhart & Wünsch, 2007). An app is developed based on Microsoft Power Apps for quick estimation of economic benefits of DTxD. The user has to input values for the number of people available, estimated time, hourly wage of employees, and if any delays are likely to occur (Figure 9). As a result, it can be estimated how much time is being saved, cost reduction and impact of delays that can be avoided by the application of digital twin.

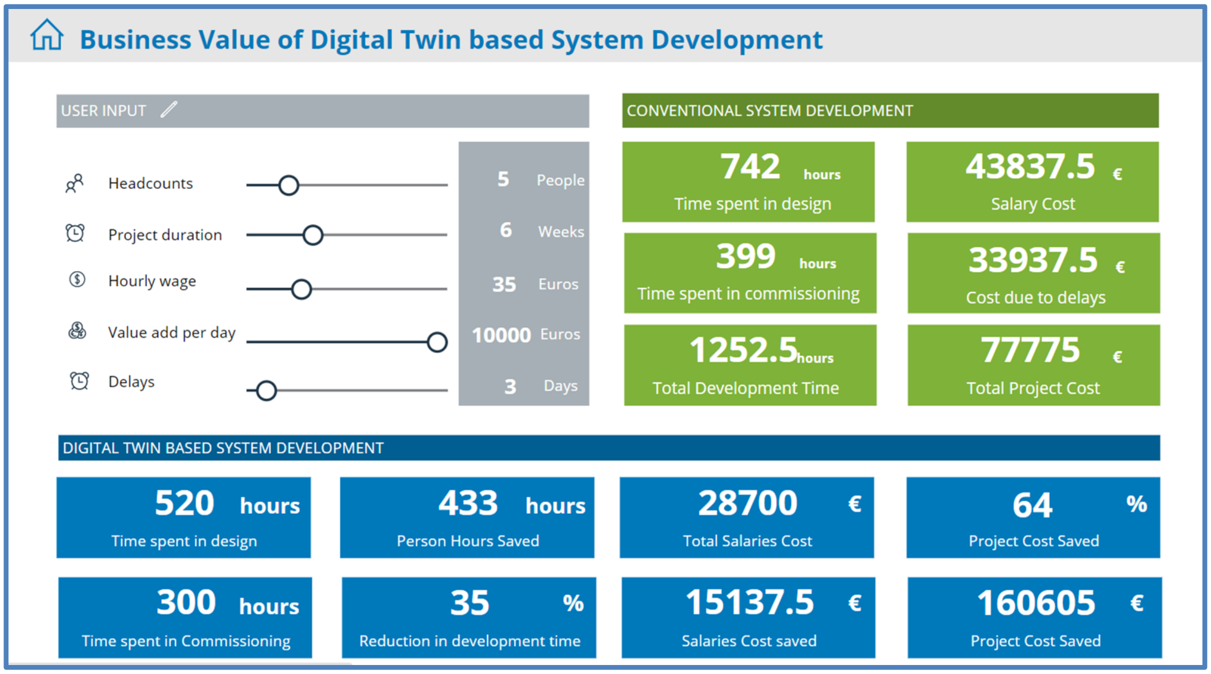

Figure 9: Tool for economic impact assessment of digital twin application.

6 CONCLUSION

The complexity of manufacturing systems is growing and conventional approaches are not valid anymore. The conventional approaches of system development need to be changed by the new approaches of virtual system design, validation and commissioning. Instead of sequential development, the steps must be used in parallel. Digital twin technology, enabled by the advancement in virtualization, communication and sensing technologies, is enabling the development of high-fidelity digital twins of complex systems. These digital twins have the potential to be used as virtual platforms to test the design, verify and validate any new strategy before implementing it in the real world. The proposed use case presented a 35% decrease in the development time. Additionally, the reconfiguration effort is reduced which works along the lifecycle of the manufacturing system. Emerging technologies such as virtual and augmented reality, artificial intelligence and explainable A.I. can be combined with digital twins to improve their usability.

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