Digital Twins for Virtual Commissioning and their effects on projects for Agile Manufacturing Systems

1. Abstract

The virtual commissioning of customer-specific machines (thus special purpose machines) has the greatest leverage in terms of improving product quality, costs and throughput time. Until now, model creation has been costly and uneconomical due to the lack of mechatronic modular building block systems.
The effects of the virtual commissioning of digital twins in series machine construction are rather small in relation to the volume of the machines to be produced, since only prototypes and product maintenance have an effect (subsequent machines will be identical design). The machines in agile manufacturing systems are always loaded automatically and are usually integrated into a higher-level production control/management system. Agile manufacturing systems [1,2,3,4] are systems for volume production with high workpiece and process flexibility. They are characterized by a parallel process (redundant machines) in one production section and a segmentation of the entire workpiece production into several sub-sections. The commissioning of the individual components and interfaces before delivery is a time-consuming and quality-defining stage under high technical stress. From this the task was derived to realize a cyber-physical model during the construction phase, which imitates reality with sufficiently exact parameters and thus can simulate a high proportion of the commissioning before the physical creation of the product. The development of a virtual commissioning for the plant components and their mechatronic and data interfaces in highly complex production systems as well as the combination of real and virtual products was the concrete challenge with the highest potentials for quality, costs and lead time of a project.

2. Introduction and Motivation

Since the fourth industrial revolution was launched under the name "Industry 4.0", a wide range of products and applications have been offered without the expected economic success. In most cases, the advantageous assistance systems, such as energy monitors, monitoring algorithms, methods for condition monitoring, etc. are seen as enablers for the distribution of production systems rather than as valuable options. For the manufacturer, their provision means costs that the operator of a production system does not want to offset, but wants to use the technology. In some cases, the seller is also unable to convey the utility value. The analysis results of the cost and benefit of digital twins [5] prior to implementation painted a significantly different picture. Relocating or splitting the commissioning will not lead to a reduction of the required volume of man-hours and was not the primary objective. A partial relocation of the commissioning process to the design and procurement phase - i.e. parallel to sections that determine throughput time - will lead to a reduction in the real commissioning and thus to an identical reduction in the project throughput time. It was also known that the number of repetitions of the function tests allows conclusions to be drawn about the quality of the PLC program. With the digitalization of the commissioning, function tests can also be automatically repeated more often without the presence of an operator. By identifying so-called sporadic errors and eliminating them during virtual commissioning, the subsequent unplanned expenditure for error elimination after delivery is reduced (empirical values: error elimination in engineering 1 hour, on the real machine at the manufacturer 1 day and on the construction site at the customer 1 week). A system supplier with turn-key competence also purchases system components from third parties, which have to be delivered for a preliminary acceptance, installed and commissioned with the interface partner (machine/robot, machine/measuring station, robot/roller conveyor, etc.). A very high proportion of the commissioning share is not used for the normal plant functions (20%), but for the investigation of all conceivable incidents (emergency stop, crash) as well as filling and emptying during type changeover (80%). This could be dispensed with by mutual exchange of the models for commissioning in "mixed reality" operation (interface test with a real product and a virtual shadow of the other product). From the experience with the digital process twin, which has been in use for several years, it was clear how quickly a path- and time-optimized NC program can be put into operation without collision risks. The digital process twin is a workarea model and simulates the axis movements, the process-relevant non-productive times, the clamping device, the machining workpiece and the required cutting tools. Compared to a PLC commissioning, the NC commissioning is very short but with clear quality and time advantages in the result and was therefore also one of the motivations for developing the Digital Product Twin for virtual commissioning. In the course of improving quality and increasing efficiency during engineering of complex machines, the mechatronic approach has proved to be the best lever, in which components are created in parallel as mechanical, electrical and fluid-technical models, thus achieving a high level of standardization. The products are created from individual mechatronic components on a project-specific basis: machines, automation, work stations, measuring equipment, etc. Fast ramp-up and earlier SOP (Start of Production): each production week earlier or each steeper plant ramp-up means higher sales for the customer and contributes positively to the result.

3. State of scientific knowledge

The use of digital twins has been analyzed in several assessments with regard to: economic applicability, type of simulation time base, modelling languages or tools and methodology [ ]. In the following the efforts and benefits of their use for the project execution of Agile Manufacturing Systems (fig.2) will be shown. The machines (fig.1) for the systems will be assembled from a modular kit and will be equipped according to the given customer specification.

3.1 Fields of application and use of Digital Twins in project execution and delivery

The field of applications during the project execution, beginning with the sales process up to the start of production (SOP), requires different specifications for such digital models. In the sales process the customer enquiry will be considered regarding the part manufacturing process, the required capacity and the requested layout. The specification will be priced but the models for the proposal process will use the standard modular system of building blocks for the individual machines. The match with the required speed of the application engineering phase the models used for simulation should be rather basic and accurate enough to provide the correct information about cycle time, machine count, correct layout configuration and the overall line performance. With the purchase order and the engineering of the mechatronic design information the Digital Product Twin according to the customer specification will be developed. During the project execution there are different milestones for verification of the simulation as well as the optimization until the final acceptance (FAC) has been achieved (fig. 3). With the finalization of the project all Digital Twins should be updated and will present the virtual copy of the real scope of supply.

3.1.1 The Digital Process Twin

The digital process twin is a work area model (fig. 4) and simulates the axis movements, the process-relevant non-productive times, the clamping device, the machining workpiece and the required cutting tools. Compared to a PLC commissioning, the NC commissioning is very short but with clear quality and time advantages.

3.1.2 The Digital Product Twin

The Digital Product Twin is a cyber physical model with close to 100 % functionality in combination with an emulated (Software in the Loop (fig. 5 - SiL)) or real control (Hardware in the Loop (fig. 6 - HiL)). In addition to the real controller other real products such as valve stacks, actors or interfaces can be connected e.g. via the "Ethernet [11]"or "PROFIBUS/PROFINET [12]". In comparison the application based on Hardware in the Loop has been evaluated the best practice solution due to its most accurate copy of the reality (fig. 7). The machine controller (e.g. SIEMENS 840 Dsl) will be connected directly with the real fieldbus to the PC (e.g. Windows with TwinCAT 3.1) on which the simulation model of the machine is installed. The simulation runs in real time [13].

3.1.3 The Digital Production/System Twin

The Digital Production/System Twin represents the complete installation of a manufacturing/production system as a model. The main purpose of this application is to analyze and optimize the material flow and the calculation of the achievable productivity or OEE (overall equipment efficiency) for the complete system [fig. 8]. Both parameters – system throughput and system performance – are contractual obligations and require a simulation model to confirm the specification. With more sensitivity for energy and environment and the investment and operating costs for these topics, simulation models are used to determine power consumption, required connected loads, media consumption (coolant, compressed air, plant water) as well as exhaust air and filter performance.

3.2 Virtual Commissioning of Agile Manufacturing Systems

Most of the customers with high volume production issue detailed project specification to take advantage of already trained personnel and existing spare part stock with their inquiries. For the system supplier requires such a specification a quite significant engineering work for their standardized modular machine components as well as for the manufacturing process. For each project an intensive commissioning phase has to be considered to supply the requested quality and meet the safety specifications. To avoid a maximum amount lead time dependent commissioning the development of virtual commissioning and commissioning as a mix of real equipment with virtual equipment offered significant advantages which are most beneficial to supplier as well as to customers. The more accurately a model reflects reality, the higher its quality which is a guideline for Digital Product Twins to be able to simulate reality.
In the future the Digital Twin will become part of the delivery or service and is therefore to be ordered and paid by the customer. This requires a definition of the simulation quality of a Digital Twin, a specification and measures of a validation of such quality [14].

3.2.1 Creation of the models for Virtual Comissioning (VIBN)

Mechatronic design of components and machines is required to enable efficient model design. The resulting 3D designs of the mechanical machines with the corresponding circuit, flow and pneumatic plans can be read into the software for model creation. The individual assemblies are then assigned the degrees of freedom and the functional parameters (e.g.: maximum travel speed, acceleration and jerk values) in the model. In this way, each element of the machine receives the known functional parameters to simulate the real component. In the first step, the PLC program, which is also provided, is compared with the model and checked for plausibility [fig. 9]. The first errors can already be detected and eliminated at this point. If devices are not addressed by the program or if the program addresses devices that are not present, then there are obvious design errors that in the past were not discovered until the real commissioning and were most likely copied in all machines built. Since the model is created during the design phase as an additive activity, the risk of missing recursion, i.e. later changes in the engineering department are being developed in earlier models are not maintained, has to be managed.

3.2.2 The Virtual Commissioning of the individual system components with the Digital Product Twin Hardware in the Loop (HiL) vs Software in the Loop (SiL)

The virtual commissioning is an anticipation of the PLC program test which is finally performed on the real machine. The aim of commissioning on the model is to shift as much time as possible from the area of the real commissioning relevant to lead time to parallelization with the engineering, procurement and production of the sub-assemblies. With a successful transfer the lead time of a project (for system business approx. 12 months until ex works) can be significantly shortened (manufacturing systems with CNC-machines only approx. 4 weeks; manufacturing cells with machines and automation (see section 3.2.3) approx. 12 weeks). Not all functions can be transferred to the virtual commissioning dependent on the customer specification and CE manufacturer's declaration which does not consider the latest simulation technology. The functionality which will be tested with the simulation model is listed in figure 10. To be able to avoid reruns for the real commissioning the model has to be as accurate as possible to the real machine. To support this request the Hardware in the Loop (HiL) test equipment supplies the best coverage (fig. 7). In addition to testing the functions on the model without any risk of damage, the simulation offers an automatic repetition of functions at the unmanned station. In manual test mode, a function is released after a small number of error-free repetitions. In automatic mode, after delivery, there are singular standstills due to a unplanned stop or crash of the PLC program. Detecting each of these sporadic errors in advance provides noticeable effects in costs (time factor of error correction at the simulator vs manufacturer's plant vs customer's plant: 1:8:40) and software quality. The simulator can be used between delivery and the start of commissioning in the customer's plant to close open issues from pre-acceptance or continue with further program optimization.

3.2.3 The commissioning of the interfaces between the connected components of an Agile Manufacturing System in reality or mixed reality

The combination of a real robot with a virtual gripper and the representation of the common functional system by means of virtual reality has been state of the art for years [15] and has opened up a new field of application for simulation models. In turn-key plants such as Agile Manufacturing Systems, several suppliers are always involved (Fig. 11: Agile Manufacturing Cell with gantry automation and CNC-machines). For commissioning and preliminary acceptance, the two system components built in spatially separate locations had to be physically brought together for the start-up. Unless very conservative end customers insist on this costly and time-consuming procedure, only advantages could be achieved by connecting a real system component to a simulation model (hardware in the loop) via e.g. the PROFIBUS interface [16]. In reality, this was immediately measurable during commissioning after installation in the operator's plant. In addition to the quality improvement of the PLC program, costs and time could be saved by not having to merge the two systems components.

3.2.4 Commissioning of the production management system

Once the installed system in customer's plant was ready to start production the production system had to be integrated into the customer's production management computer system. Next to the standard production process also the ramp-up and –down per part type and variant has to be demonstrated to adjust the production management system with the installed new production line. The use of a production-ready production system for a longer period of time (weeks) for integration into a plant production system can now be avoided due to the availability of virtual models and will support an earlier start of production (SOP)

4. Results

The introduction of the simulation technology for Agile Manufacturing Systems was a multi-year procedure with the requirement to modify the engineering process to a mechatronic approach to allow the model creation already during engineering. With the complete new approach and the application of this technology for project execution the effectiveness has permanently increased with the learning curve and has reached a perfection where internal results were far more beneficial as the development. The ROI of such projects is less than 1.5 years. In parallel the advantages have been recognized by the customers in several aspects and those will provide additional value. In combination of both sided benefits the virtual commissioning with the Digital Product Twin is a best practice for a win-win-project.

Lead time reduction (Fig. 12) is a first measurable effect which will be a benchmark against the traditional project execution: 12 to 14 months until ex-works and 6 to 9 months installation until start of production. With the virtual commissioning the lead time can be shortend by 5 (CNC machines only) to 13 (machines, automation commissioning with mixed reality) weeks until ex works and 8 weeks on site plus another 8 weeks for the system integration to a host computer system for production management.

Quality improvement is definitely achieved in different areas and will be quantified in a product cost reduction

Cost reduction can be measured for several areas:

a) unscheduled installation work caused by late detection of engineering errors and theirs correction in finished built components, for the manufacturing process commissioning motorspindles had to be replaced due to collision by running-off the CNC programs and during process optimization. The process simulation has wiped-off such a waste.

b) relocation of expenses from high capital commitment (real commissioning) to a time of low capital commitment using virtual commissioning (fig. 13),

c) reduction of project costs by shortening the lead time in the manufacturing plant and during installation in the customer plant

5. Conclusion and Outlook

The virtual commissioning of customer-specific machines (thus special purpose machines) has demonstrated the greatest leverage in terms of improving product quality, costs and throughput time. Until today there are still 3 Digital Twins required for the production system business (Digital: Process Twin, Product Twin and Production/System Twin) due to the different applications in task and project maturity however with some relations to each other, such as CNC-program simulation on the Process Twin and on the Product Twin or the simulation of the automation In the production/system model and as a product model. With further software development and a more models available the next future may allow the merge into one Digital Twin but the emulation of the controller has to improve to achieve a one matches all without Hardware in the Loop.

The significant advantages for green field projects will initiate further business models for service such as retool and reconfiguration of systems as well as remote services. The Digital Product Twin is a perfect training tool with a real HMI and control panel with a 3D animation of the machine with all features and movements.

With the establishment of the concept of the Digital Twin modelling and simulation will be applied increasingly in all life cycle phases of a machine or production system [14].

A quantum leap will be achieved, when machines in the field will be connected to a network, which will provide data for the simulation models and the models will optimize the parameters by the methodology of artificial intelligence. A business model that is currently experiencing strong growth is condition monitoring in the sense of preventive maintenance. By linking the real product to the simulation model, the necessary measures can be determined at the Digital Twin.

The concluding step is then close to grasp with the determination of certain parameters for predetermining events for prescriptive analytics (fig. 14).

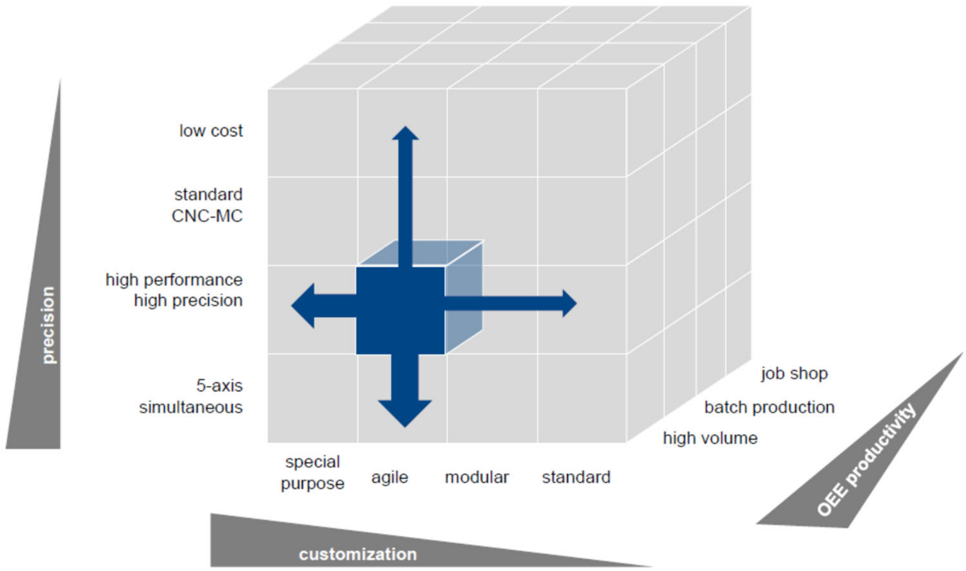

Figure 1: CNC-machines for Agile Manufacturing Systems – matrix segmentation in relation to manufacturing precision, customization and required productivity level

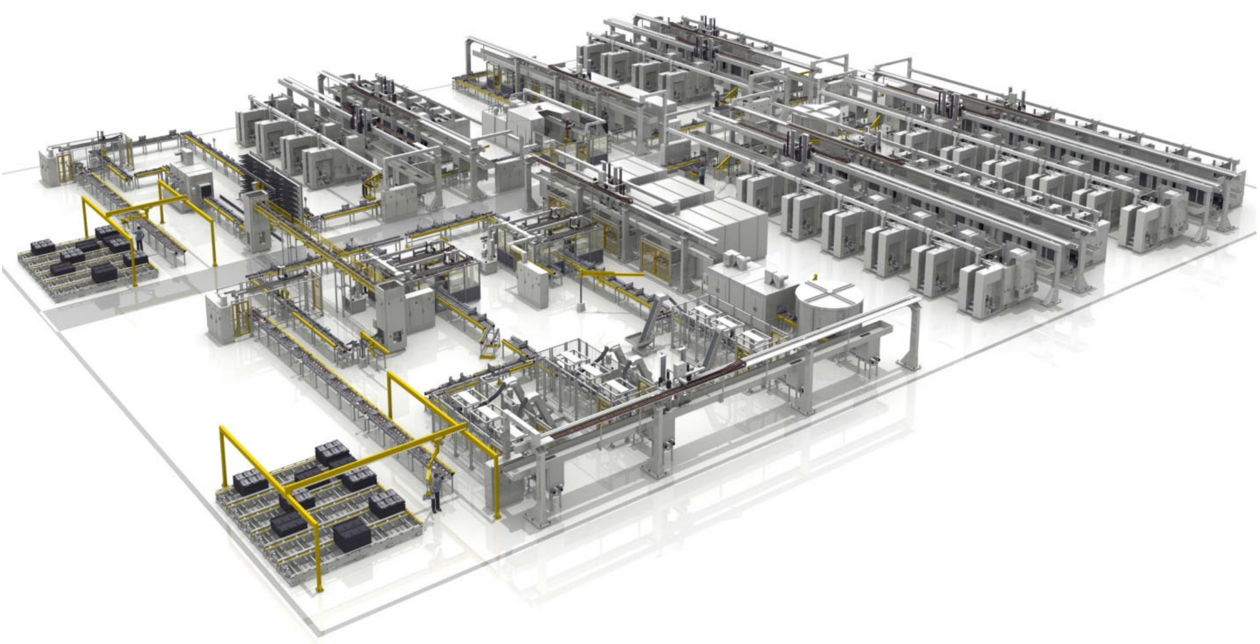

Figure 2: Agile Manufacturing System (System for cylinder head machining, 300k parts per annum) with a parallel process within the cells (one automation segment) and sequential process between the cells (different machine configuration)

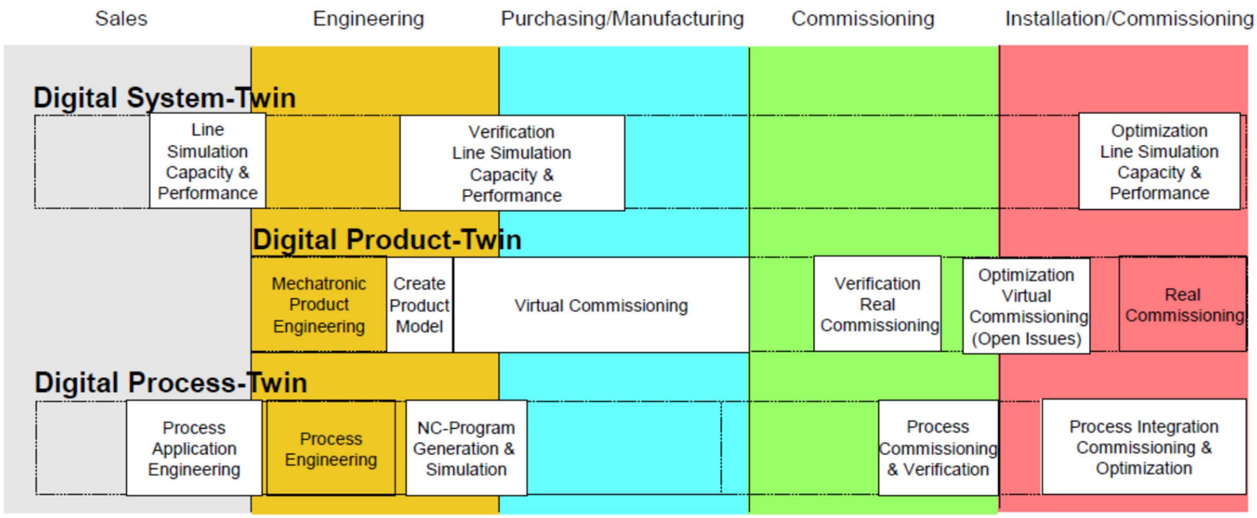

Figure 3: Field of application for the individual Digital Twins during the project execution and their modifications and optimization in relation to the project schedule

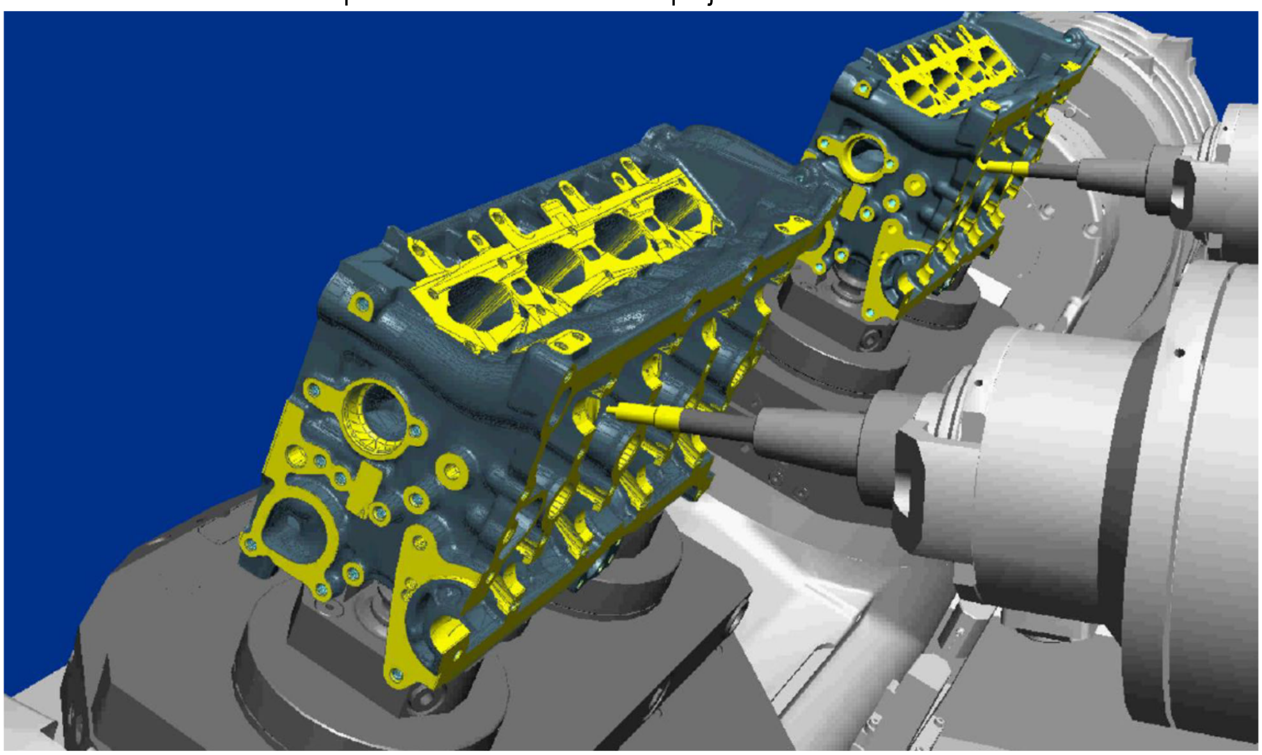

Figure 4: Digital Process Twin for a cylinder head process on the dual spindled machine SPECHT 500 DUO with adaptor plates

Figure 5: Digital Twin – Software in the Loop SiL

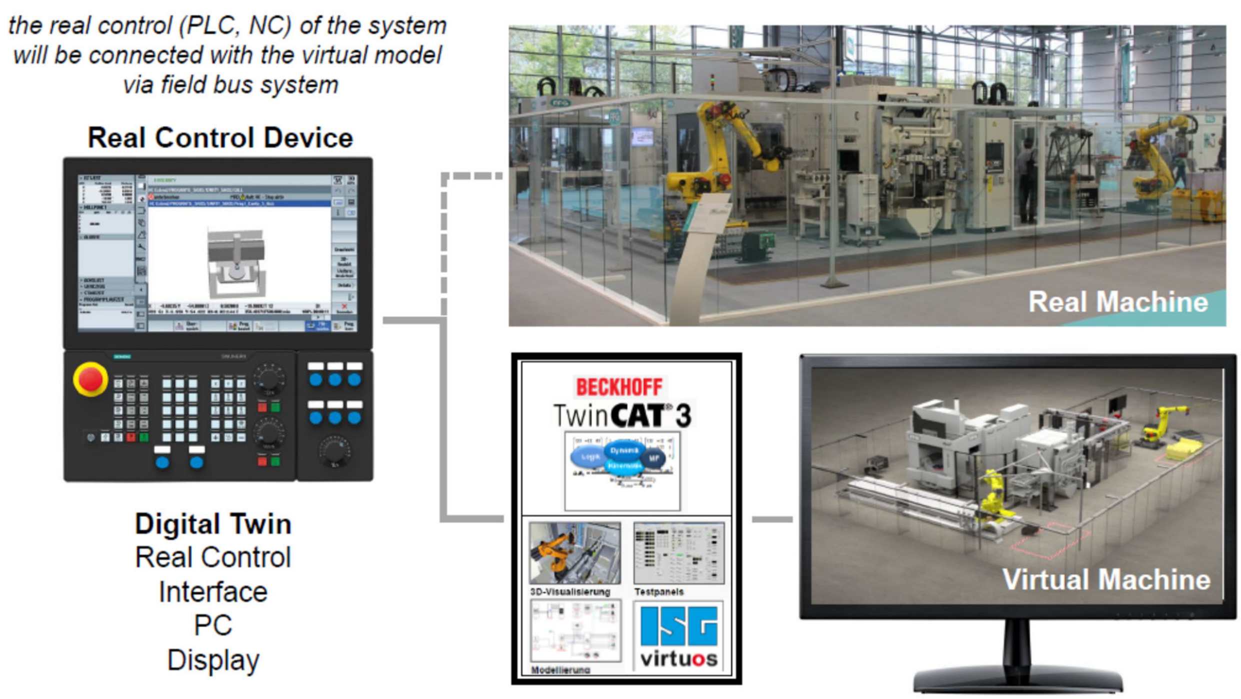

Figure 6: Digital Twin – Hardware in the Loop HiL

	Hardware in the Loop (HIL)		Software in the Loop (SIL)
	Real Control Devices are connected with a PC via Beckhoff Interface ISG Virtuos Software: modell creator, animated virtual machine (3D visualization), test panels Beckhoff Twin CAT Software: Virtuos generates a target system with Twin CAT, parameter and cylcle times via manual input Display with real time visualization of machine tool activities		PC will simulate digital twin based on software ISG Virtuos Software: modell generator, animated virtual machine (3D visualization), test panels Control Device Simulation Software: currently available with FANUC CNC Guide and SIEMENS Sinumerik One, Virtuos connects automatically with the controls software, I/O definition will be done manually
+	real-time simulation with control hardware in the loop	+	no controls hardware required (cost)
+	Interfaces for other tennants in the communication loop can be established	+	Digital Twin and emulated controller runs in one system
+	testing of new hardware components via hardware connection available	+	configuration in one computer ==> mobility, demonstration at customer's place
+	deterministic real-time simulation (with Virtuos) ==> identical cylcle times as in reality	+	utilization at engineer's desk - no lab installation required
+	hardware components can be connected to the digital twin to be commissioned individually prior to machine tool availability	+	currently only FANUC available (SIEMENS Sinumerik One not officially released)
		-	cycle time of emulated control system is slower than real control system

Figure 7: Comparison between Hardware-in-the-Loop (HiL) and Software-in-the-Loop (SiL)

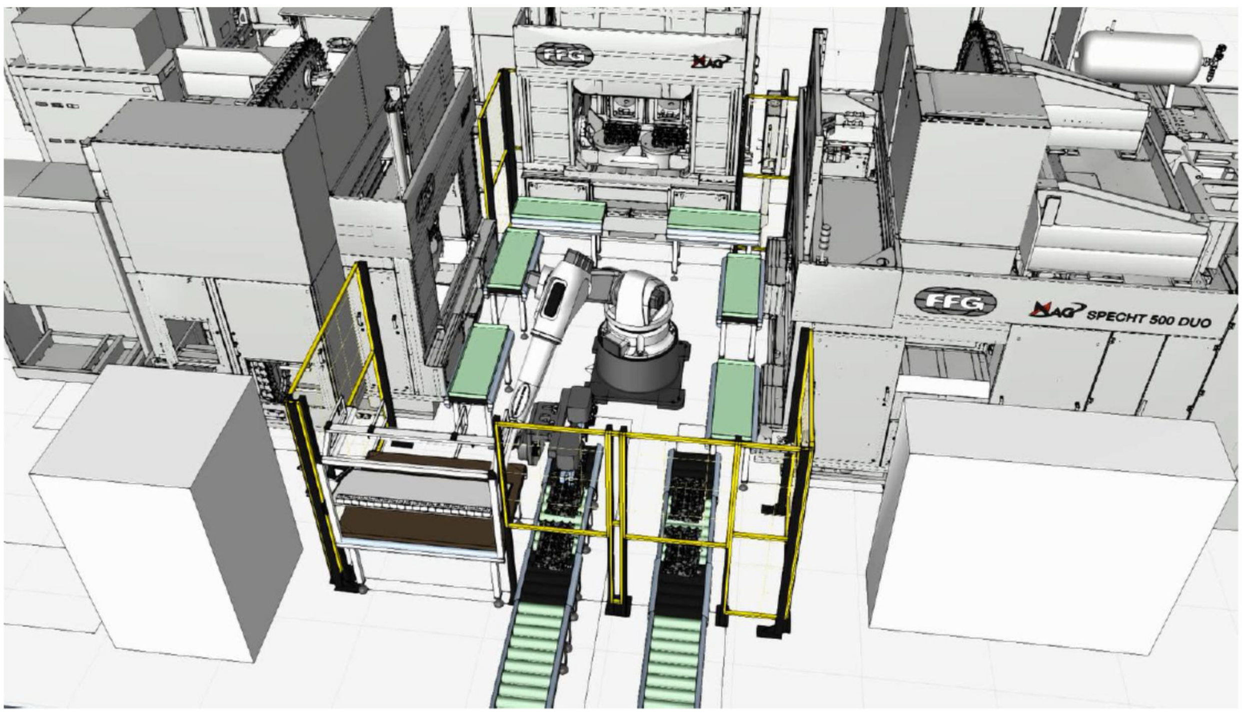

Figure 8: Digital Production/System Twin: Simulation model of a complete production system or a production cell (selected software: 2D: Plant Simulation (SIEMENS) and 3D: Visual Components (Visual Components) shown above)

Steps for 3D-Visualization

- ❑ Adjustment and simplifying design data
- ❑ Import of the optimized CAD data
- ❑ Kinematizing of the individual components
- ❑ Link of the CAD nods with the components in the simulation software

Steps for Modeling and Parmeterization

- ❑ Simulation of the hydraulic and pneumatic functions
- ❑ Simulation of the circuit diagram
- ❑ Reproduction of components such as spindle collet, pumps, door switches, hatches, …
- ❑ Creation of the kinematic functional chains
- ❑ create and configure the interfaces to the bus connection

Start Conditions for Model Creation

- ❑ Complete fluid and hardware design documents
- ❑ Supply of all CAD product data
- ❑ Information on additional functions

- ❑ Completed hardware design
- ❑ Defined machine data set
- ❑ Availability of the PLC program for the product

Figure 9: Preconditions and individual steps for model creation (Hardware in the Loop)

all projects

- machine start-up function chain
- protective /s afety doors
- emergency stop functions
- axis functions
- home position
- clamping/releasing functions
- check error texts
- loading hatch function
- recording CNC / ghost
- operating functions

project specific

- cutting tool change
- clamping functions
- unload spindle/magazine
- test abort situations
- HMI functions
- chip removal system
- SE-CS NC cycles
- loading cutting tools
- cycle time optimization if necessary (portals)
- process optimization (gantries)

partially or not done

- safety
- axis drives
- read part tracking data (only with HW)
- test interfaces
- support power units (high pressure, hydraulic, chiller, etc.)
- media supply functions (e.g. minimum quantity lubrication (MQL))
- blow off / flush
- material cutting

Figure 10: definition of functions for the virtual commissioning dependent on the type of Digital Twin

Figure 11: Manufacturing Cell with gantry automation and dual spindle CNC machines DPECHT 450 DUO installed in the customer plant where both components were merged first time physically but commissioned in different locations in a mixed reality procedure

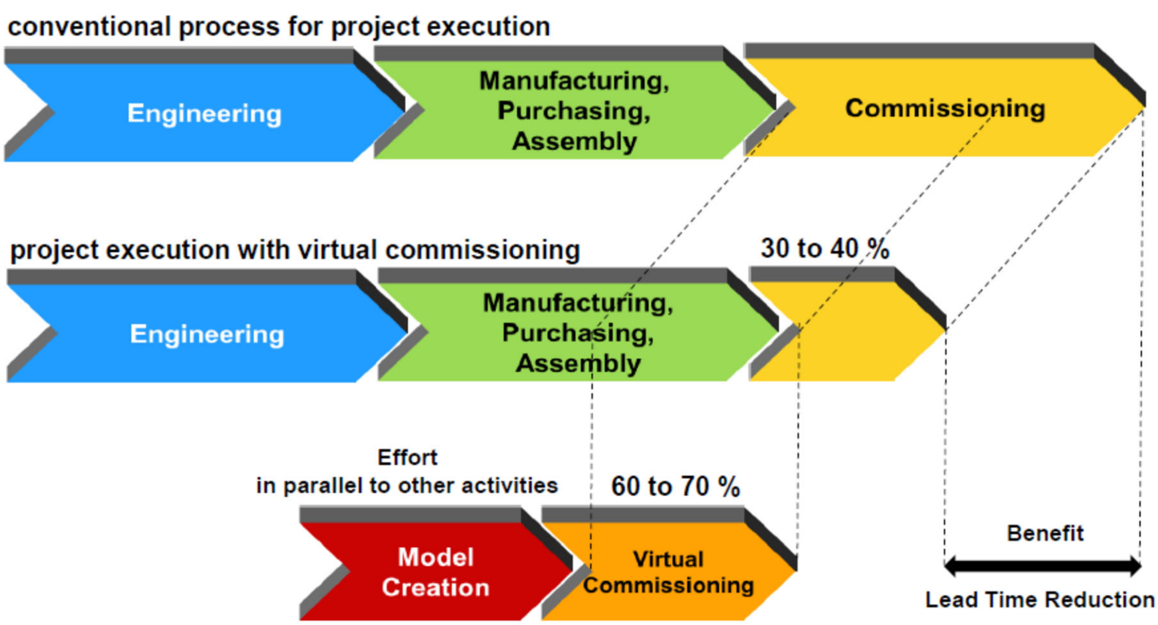

Figure 12: Lead Time Reduction as one benefit of the virtual commissioning prior to the real commissioning [10]

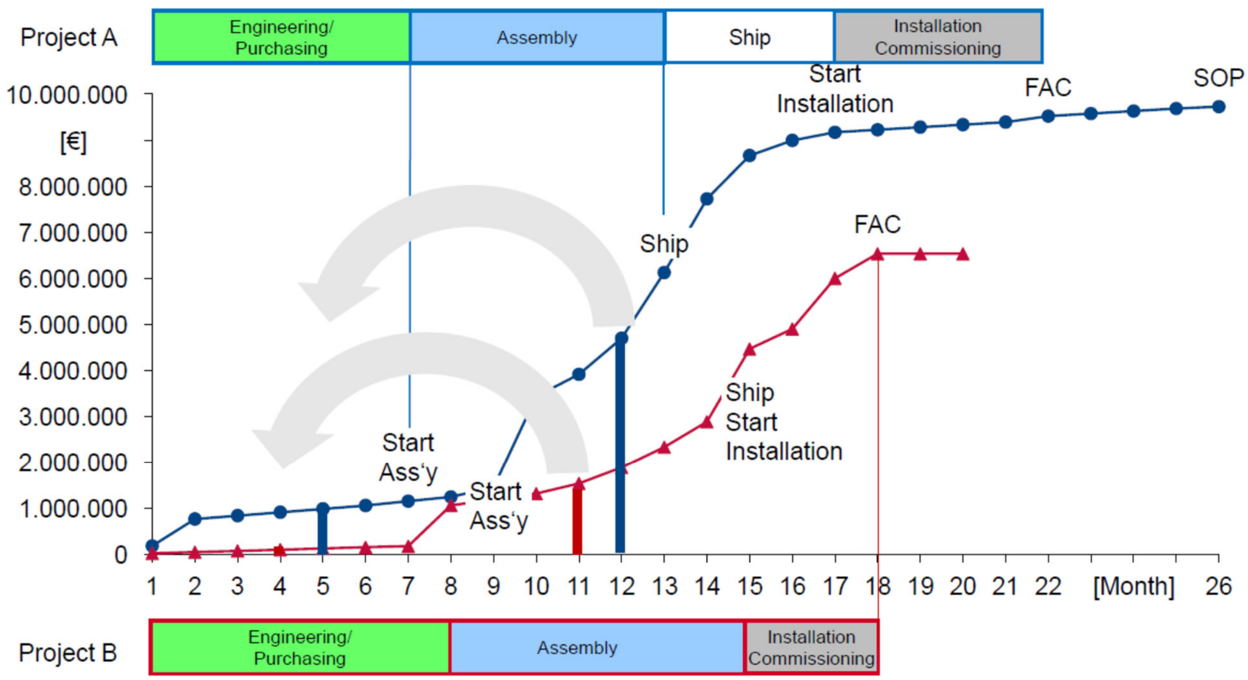

Figure 13: Project spend curves for (2) smaller Agile Manufacturing Systems with the real commissioning in month 11/12 and the transfer of a virtual commissioning in month 5

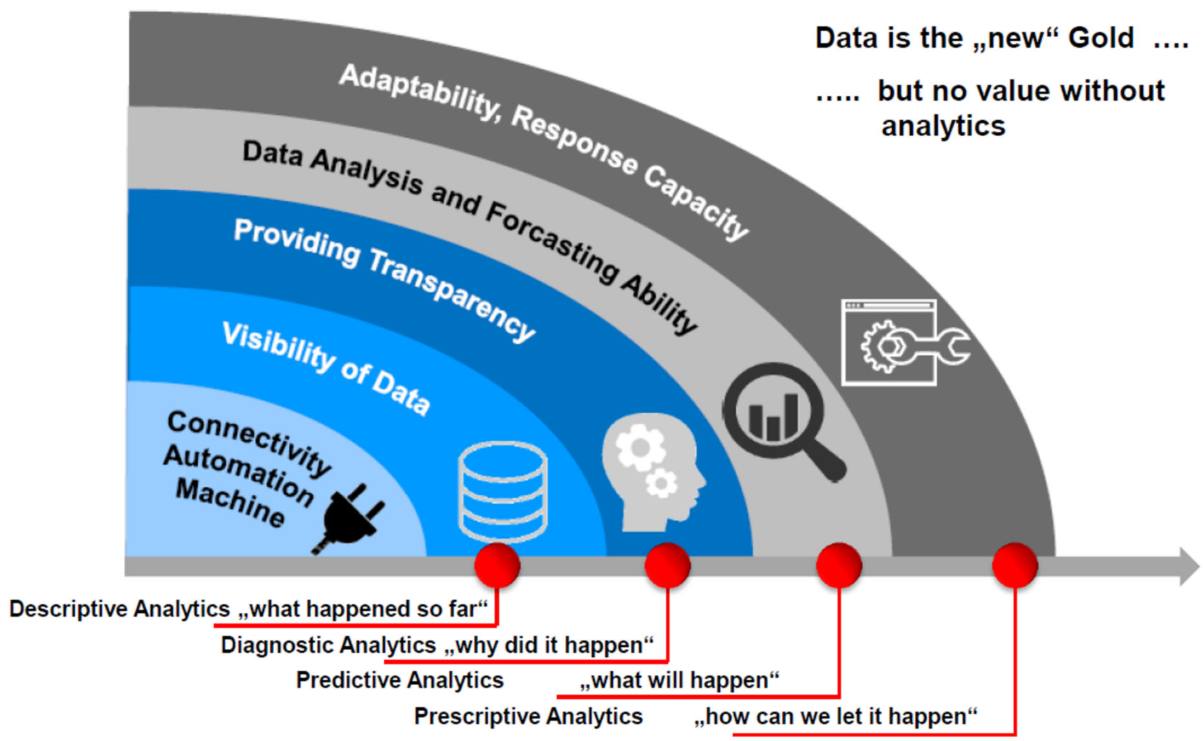

Figure 14: Onion peel model for stepwise intelligent data processing from the production machine for use in new business models. The goal is to achieve "Prescriptive Analytics" for use in OEE optimization of agile manufacturing systems with the simulation on a Digital Twin

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