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About The Importance of Autonomy and Digital Twins for the Future of Manufacturing

Roland Rosen*, Georg von Wichert*, George Lo, Kurt D. Bettenhausen****

*Siemens AG, Corporate Technology, Munich, 80200, Germany
(e-mail:roland.rosen@siemens.com; georg.wichert@siemens.com)
**Siemens Corporation, Corporate Technology, Princeton, NJ 08540-6632, USA
(e-mail: george.lo@siemens.com; kurt.bettenhausen@siemens.com)

Abstract: Industrie 4.0 – the "brand" name of the German initiative driving the future of manufacturing – is one of several initiatives around the globe emphasizing the importance of industrial manufacturing for economy and society. Besides the socio-economical if not political question which has to be answered – including the question about the future of labor – there are a couple of substantial technical and technological questions that have to be taken care of as well.

Keywords: Digital Twin, Autonomy, Manufacturing, Automation, Simulation.

1. INTRODUCTION

Many articles and publications focus on the importance of digitalization, modularity, networks and connectivity in the automation context, enabling the next generation of collaborative production networks to better adapt to an increasingly dynamic market.

In order to be able to respond quickly to unexpected events without central re-planning, future manufacturing systems will need to become more autonomous. **Autonomous systems** are intelligent machines that execute high-level tasks without detailed programming and without human control. They know their capabilities (that are modeled as "skills") and their state. They are able to decide between a set of alternative actions, orchestrate and execute skills. In order to make this happen, the autonomous systems will need access to very realistic models of the current state of the process and their own behavior in interaction with their environment in the real world – typically called the "**Digital Twin**".

A consequence of autonomy is the sharp increase in complexity of ensuring the proper system behavior during the course of production in order to reach the desired production goal. This can only be reasonably achieved by extensive use of model based **simulation** not only during design and planning, but also during the other phases of life cycle for such purposes as diagnosis and optimized operations.

This paper focuses on the importance of all four aspects driving the future of manufacturing: Modularity – Connectivity – Autonomy – Digital Twin.

2. CHALLENGES

Increasing digitalization in every stage of manufacturing is opening up opportunities for manufacturers to achieve a whole new level of productivity. This begins with modularity in the design of products and production modules, leading to greater effectiveness in engineering of the production system. Autonomy provides the production system with the ability to respond to unexpected events in an intelligent and efficient manner without the need for re-configuration at the supervisory level. Lastly, ubiquitous connectivity such as the Internet of Things facilitates closing of the digitalization loop, allowing next cycle of product design and production execution to be optimized for higher performance.

The enabler to achieve all these is the Digital Twin, a notion where the information created in each stage of the product lifecycle is seamlessly made available to subsequent stages (see Figure 1).

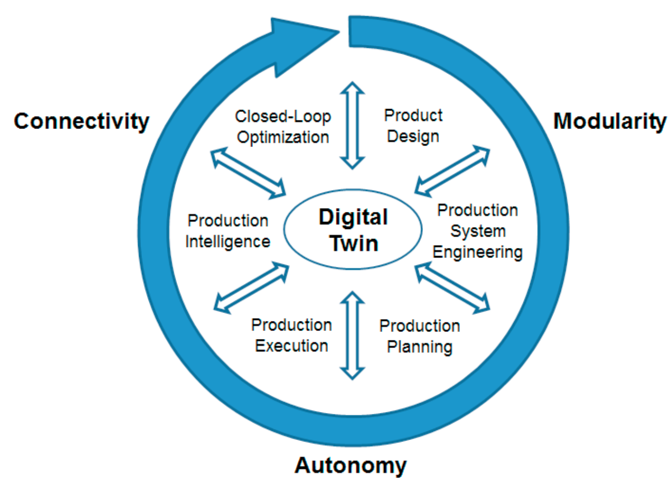

Figure 1: Notion of the digital twin in the lifecycle of a product

3. DIGITAL TWIN SIMULATION APPROACH

Digitalization can be understood as "integration of digital technologies into everyday life by the digitization of

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everything that can be digitized" (Business Dictionary, 2015). Transferred to the life cycle of products and systems in an industrial context, this leads to the increasing creation, use, and storage of digital artifacts of all kinds. These artifacts contain all information and data that are needed by different stakeholders and form a huge digital data storage. The Digital Twin is not just a big collection of all digital artefacts, it has a structure, all elements are connected and there exists meta-information as well as semantics.

From a simulation point of view the Digital Twin approach is the next wave in modeling, simulation and optimization technology (see Figure 2). In the last decades, simulation developed from a technology being restricted to computer and numeric experts to a standard tool commonly and everyday used by engineers to answer specific design and engineering questions. Today, simulation is the basis for design decisions, as well as validation and test not only for components but also for complete systems. It is even developing further - "communication by simulation" is the core concept of model-based systems engineering (MBSE), an emerging trend in systems engineering. Still, simulation is mostly considered to be a tool for R&D departments. Extending simulation to subsequent life cycle phases as a core product / system functionality, e.g. delivered before the real product itself or supporting the operation by simulation-driven assistance, is the next big trend in simulation.

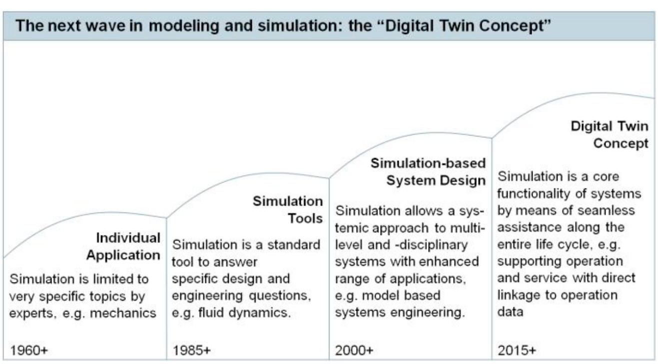

Figure 2: The Digital Twin - the next wave in Simulation Technology

3.1 Concept of Twins

The concept of using "twins" is rather old. It dates back to NASA's Apollo program, where at least two identical space vehicles were built to allow mirroring the conditions of the space vehicle during the mission. One vehicle remaining on earth was called the twin. The twin was used extensively for training during flight preparation. During the flight mission it was used to simulate alternatives on the earth based model, where the available flight data were used to mirror the flight conditions as precise as possible, and thus to assist the astronauts in orbit in critical situations. In this sense, every kind of prototype, which is used to mirror the real operating conditions for simulation of the real time behavior, can be seen as a twin.

Another form of a "hardware" twin is the "Iron Bird", a ground-based engineering tool used in aircraft industries to incorporate, optimize and validate vital aircraft systems (Airbus Industries, Innovation 2015). Due to the increasing power of simulation technologies more and more physical components are replaced by virtual models in the Iron Bird. This allows for using the concept of an Iron Bird in earlier development cycles, even when some physical components are not yet available. Extending this idea further along all phases of the life cycle leads to a complete digital model of the physical system: the Digital Twin.

The term Digital Twin was brought to the general public for the first time in NASA's integrated technology roadmap under the technology area 11: Modeling, Simulation, Information Technology & Processing (NASA Technology Roadmap, 2010 and 2012). It was outlined as "A Digital Twin is an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin."

3.2 The Challenge

The digital twin is a highly dynamic concept growing in complexity along the life cycle. MBSE lays the core of the Digital Twin, which is handed over together with the product or even before. During operation it is the basis for assist systems. Such software solutions support in combination with smart data approaches operators by simulation-driven forecasts as well as calculating control and service decisions. The models (also parameters) are evolving over the life time of the product or system, e.g. due to wear, in an automatic way.

3.3 Example Manufacturing

The evolutionary development, pushed forward by Industrie 4.0 (Acatech, 2013) and driven by technological ideas behind the term cyber-physical system (CPS), leads to new production concepts which need seamlessly integrated simulation models along the lifecycle and different abstraction levels in order to achieve increased competitiveness (energy and resource efficiency, shorten time-to-market, enhanced flexibility).

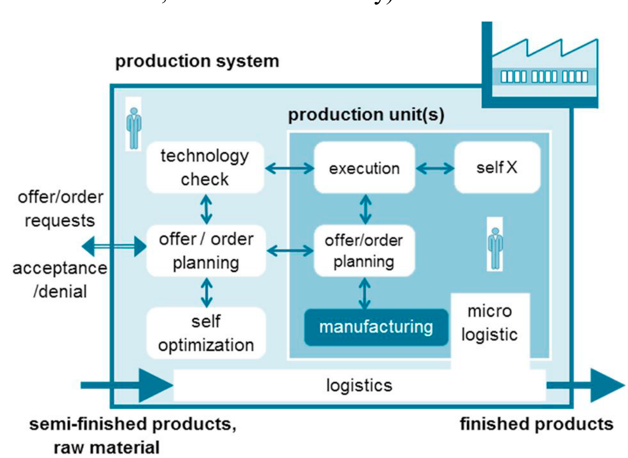

Figure 3: Architectural overview of production system with modular production units

Derived from use cases, Figure 3 shows a general architectural overview of a production system with modular production units, which illustrates new production opportunities:

- Distributed planning, shared between production units and production system. Production units can offer more detailed technology data (dynamic and static), than a generic planning system. Real-time calculations for e.g. production time, costs, required material are tasks of the production unit.
- Large numbers of offers and orders can be planned based on statistical assumptions. Continuous reaction to disturbances by automatic (re-)scheduling of the production (control loop) supports dynamic reaction.
- Improved decision support by means of detailed diagnosis and semantic context by using simulation models.
- Production units plan and execute offers/orders automatically. This is realized by simulation of the capabilities of production units, product handover, combined with visualization of process data and asset management.

These aspects directly lead to new application fields for modeling and simulation. In Figure 4 top left, a concept design model is shown, which simulates not only the 3D shape but also the movements of the robot and basic process steps of the drilling machine. With this simulation study the feasibility of functions – in the shown example to drill holes with an arbitrary angle by fixing the work piece with the robot in any position - of a new or adapted production unit can be validated. A further use of the model is the first determination of operation and changeover times.

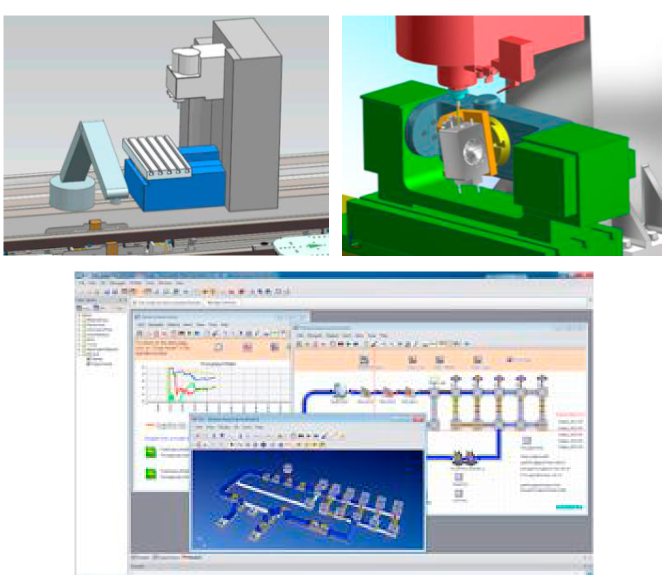

Figure 4: Concept evaluation, CAM simulation and factory planning

In the detailed engineering phase, specific simulations of the machining process (Figure 4, top right) help to develop the CAM program for the CNC machine and/or to calculate effects for the work pieces (e.g. quality), tool kit (e.g. abrasion) or machine tool (e.g. thermal stress). As the concept models are still available via the Digital Twin, the compilation of these models is facilitated. Furthermore, the consistency of the operation procedures is validated.

This reuse of existing know-how runs like a common thread through the development and the operation of the production system. Consequently all available data from the product (how is it to be produced) are stored in the Digital Twin and used for the optimization of the plant's operation (see Figure 4, bottom).

4. AUTONOMOUS SYSTEMS

Autonomous systems are machines (or groups of machines) that are able to execute high-level task specifications without explicitly being programmed (Beckey, 2005). Instead they achieve high-level goals by flexibly orchestrating a set of task independent basic or elementary capabilities. These capabilities are modeled independent of the specific task and commonly referred to as sensomotoric "skills". Such machines are the hallmark of flexible automation, since they automatically adapt to variations in environmental conditions, in the products to be manufactured, the production volumes or in response to exceptions occurring during the execution of the production process. In order to do so, they use sensors to perceive their environment and the current situation, they employ automated reasoning and planning to determine their course of action, and they use actuators to execute the determined action sequence in order to achieve the overall goals set by the governing manufacturing process.

In order to do so, the autonomous systems require as much information as possible concerning the overall world state, the products to be manufactured, the geometry and affordances of the parts and tools to be used, as well as their own capabilities and configuration. While some of this information might be inferred from the data generated by the systems sensors, most of the information (e.g. required mating forces, surface properties etc.) will have to come from different sources.

Some of the information will become available as early as in the product design, the production system design, and also during the production planning. The concept of the digital twin as introduced in the previous sections will collect all this highly important prior knowledge on the product and the production process seamlessly, and make it available to the autonomous systems actually executing selected production steps. As such, the digital twin is a core enabler of autonomy and therefore key for achieving a new level of flexibility in automation systems.

It is intended that at operation time, all information either perceived with the sensors or generated by the execution system is stored in the Digital Twin. Therefore, the Digital Twin at any time represents the full environment and process state. This information as well as the models provided by the Digital Twin will be used for the forward simulations required as part of the action planning of the autonomous system. These simulations will be used to anticipate the consequences of actions by the autonomous system in a given situation. This is of great importance for the system to take autonomous decisions over action alternatives, which is one of the foundational capabilities of autonomous systems.

This ability is what differentiates autonomous from automated systems (Zühlke, 2008). While the automated systems executed fixed, carefully engineered sequences of actions, the autonomous systems understand their tasks based on explicitly represented knowledge about the machine, the task and the environment, see for example (Tenorth et al., 2013). This allows the autonomous system to modify the course of action to react to variations in products, production volume and in the context of automatic exception and error handling without manual efforts for supervision or reconfiguration. Thus, autonomous systems are the key enablers for the new level of flexibility demanded by latest industrial automation applications.

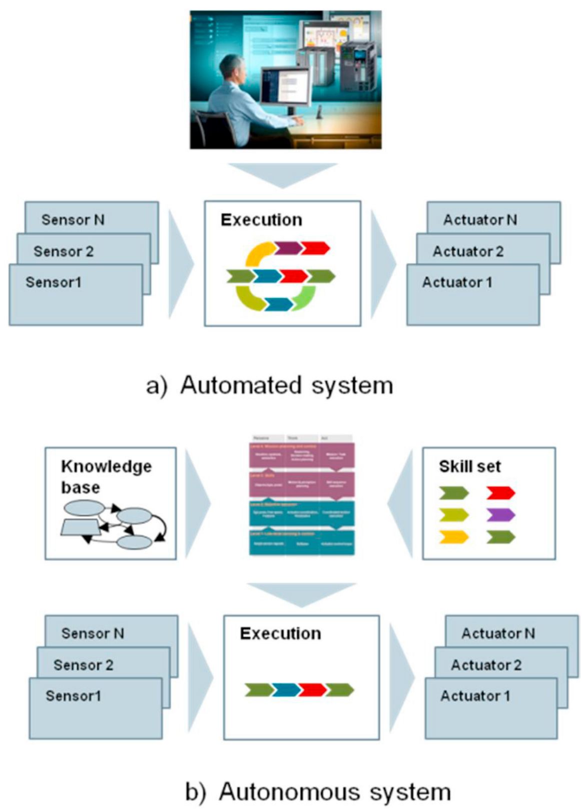

Figure 5: Difference between automated (a) and autonomous systems (b).

5. EXAMPLES OF AUTONOMY

The scenario for the examples assumes the Digital Twin is stored on the memory (e.g. digital product memory, see Wahlster, 2007) attached to the pallet carrying the physical part. This, however, is not the only way to store the Digital Twin since the example would be equally valid if the Digital Twin were stored, for instance, in the cloud. The only pre-requisite is a way to uniquely associate the physical part with its Digital twin.

5.1 Example of autonomy enabled by digital twins

Consider an example of a cyber-physical production system (CPPS) consisting of four cyber-physical production units; a Robot Load/Unload Station (including a Carousel Buffer), a CNC Drilling Machine, a CNC Milling machine and a Transport System (see Figure 6). Every production unit maintains a Digital Twin of itself; the latter contains such information as the Unit ID, skills/capabilities, configuration, current states and the pallets currently in its possession.

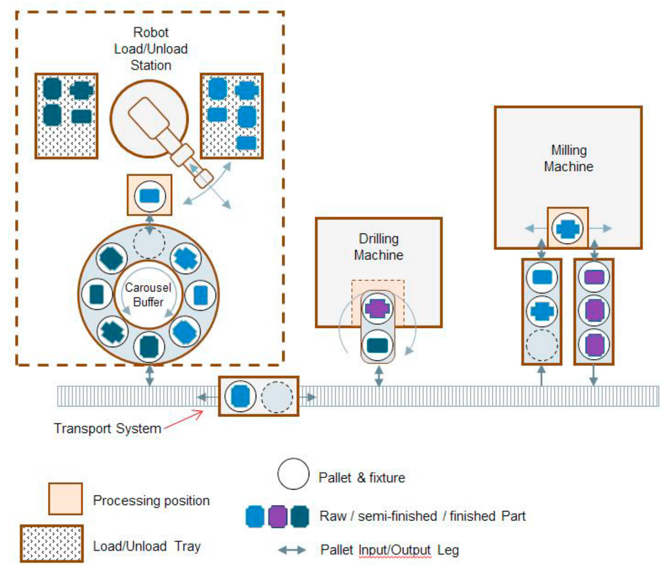

Figure 6: Example of a Cyber-Physical Production System

Every pallet maintains the Digital Twin of the part it carries on its local memory (see Figure **7**). The Digital Twin contains all information needed for the production in this CPPS, e.g.:

- Part ID and part type
- Production order number and priority
- Production workflow with such information as NC program number, skill list and tool list for each operation step
- Current states and locations
- NC program files
- Production history (e.g. which operation was done on which machine)

Frequently used information such as Part ID is stored on RFID while bulk data such as NC program file is stored on contact memory.

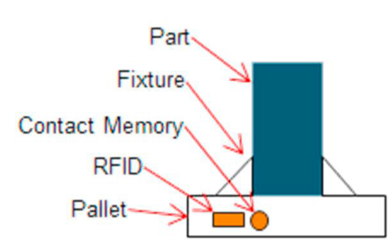

Figure 7: Example of local memory on a pallet

5.2 Example of keeping the digital twin in sync

Now consider an example of the part flow through this CPPS (Figure 8):

1. A Part is taken out of a tray and fixed onto a pallet at the load/unload station. The Digital Twin of the part is read from the memory store on the tray and written to the memory store of the pallet.
2. The pallet carrying the raw part is first brought to buffer.
3. When the milling machine becomes available, the pallet is transported to its input leg.
4. After the part has been milled, its Digital Twin is updated. It then waits in the output leg for the next operation. Note: to avoid blocking the machine, the pallet may be brought to the carousel buffer in order to make room.
5. Once the drilling machine becomes available, the pallet is brought there for processing.
6. After the part has been drilled, its Digital Twin is updated and the pallet brought to the buffer.
7. From the buffer, the part is brought to the load/unload station where it is removed from the pallet and placed in a tray. The Digital Twin of the part is then transferred from the pallet memory to the tray memory.

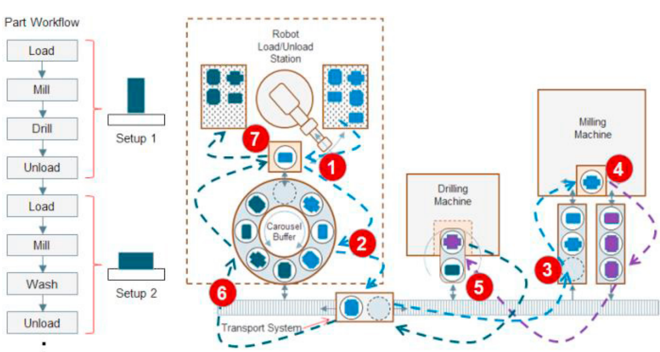

Figure 8: Example of part flow through the CPPS

5.3 Example of Autonomy in Part Flow

Normally, the part flow through the system is controlled by a central Manufacturing Execution System. By making the Digital Twins of the parts directly available to the production units, the latter can now orchestrate the part flow autonomously through, for instance, a process of negotiation (Siemens, 2014).

Take, for example, the milling operation on the part at location (4) in Figure 8 has just been completed:

- The milling machine looks at the Digital Twin of the part and establishes the next operation is drilling
- It sends a request to all machines for offers to do the drilling (i.e. to the drilling machine as well as itself since it also has drilling skill)
- It evaluates all returned offers based on pre-defined rules (e.g. cost vs. time):
- Case a: The drilling machine wins the order (should be the normal case by design), the milling machine sends a transport order to have the part brought to it
- Case b: The milling machine wins the order (because e.g. the drilling machine has a large backlog), it proceeds with the drilling operation on the part
- Case c: No machine is able to make an offer (e.g. the drilling machine is down and the milling machine does not have the tools), the milling machine sends a transport order to have the part brought to buffer

5.4 Example of Autonomy in Fault Handling

Assuming the milling machine in the example CPPS not only has the skills to mill and drill, but also the skill to buffer pallets.

Consider in this example, a breakdown of the carousel buffer (see Figure 9). This would normally cause a deadlock in the part flow because the finished part in the drilling machine has nowhere to go. Since the milling machine has a buffering skill, the transport system assigns it temporarily to be the system pallet buffer in place of the carousel buffer. Finished parts from the drilling machine can now be brought to the input leg of the milling machine for buffering, making room for semi-finished parts to be drilled. In this way, the CPPS can continue production until machining of all the parts is finished, before which time the carousel buffer should have been repaired. As soon as the carousel buffer is operational again, raw parts delivery resumes, finished parts in the milling machine evicted and the production returns to the normal state.

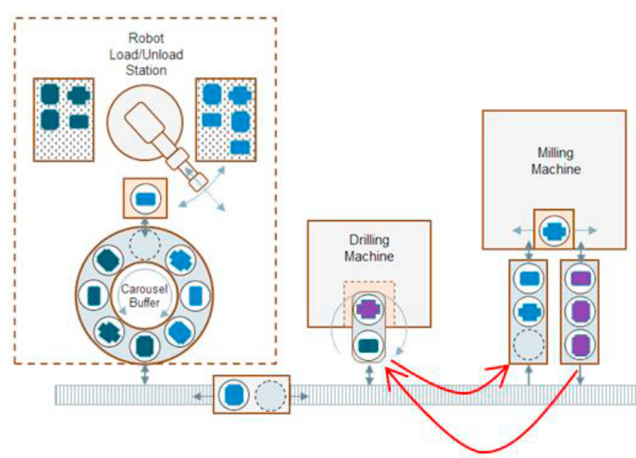

Figure 9: Example of self-adaptability

6. SUMMARY AND OUTLOOK

In the context of Industrie 4.0 and CPS modularity and autonomy are major topics. The production system and production units react autonomously on new orders, modified order priorities or disturbances during operation, to name just a few examples. In such a situation comprehensive knowledge on the current state of the production system and on its own capabilities is required. The first topic is mainly addressed by means of gathering, storing and processing all available (sensor-)data available in the production system, together with operation conditions like order quantity. However, not all desirable quantities can directly be measured and predictions to future behavior based solely on operation data are delicate especially if a flexible production system is considered. Combining the real life data with the simulation models from design allows on the other side to give good predictions based on the realistic data. This addresses the opportunities to use simulation for assist systems to support operators and planners during normal operation as well as for maintenance and service by simulation-based forecasting. The concept of Digital Twin enables exactly such a procedure, as all models and all data are available in a consistent and well aligned environment.

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